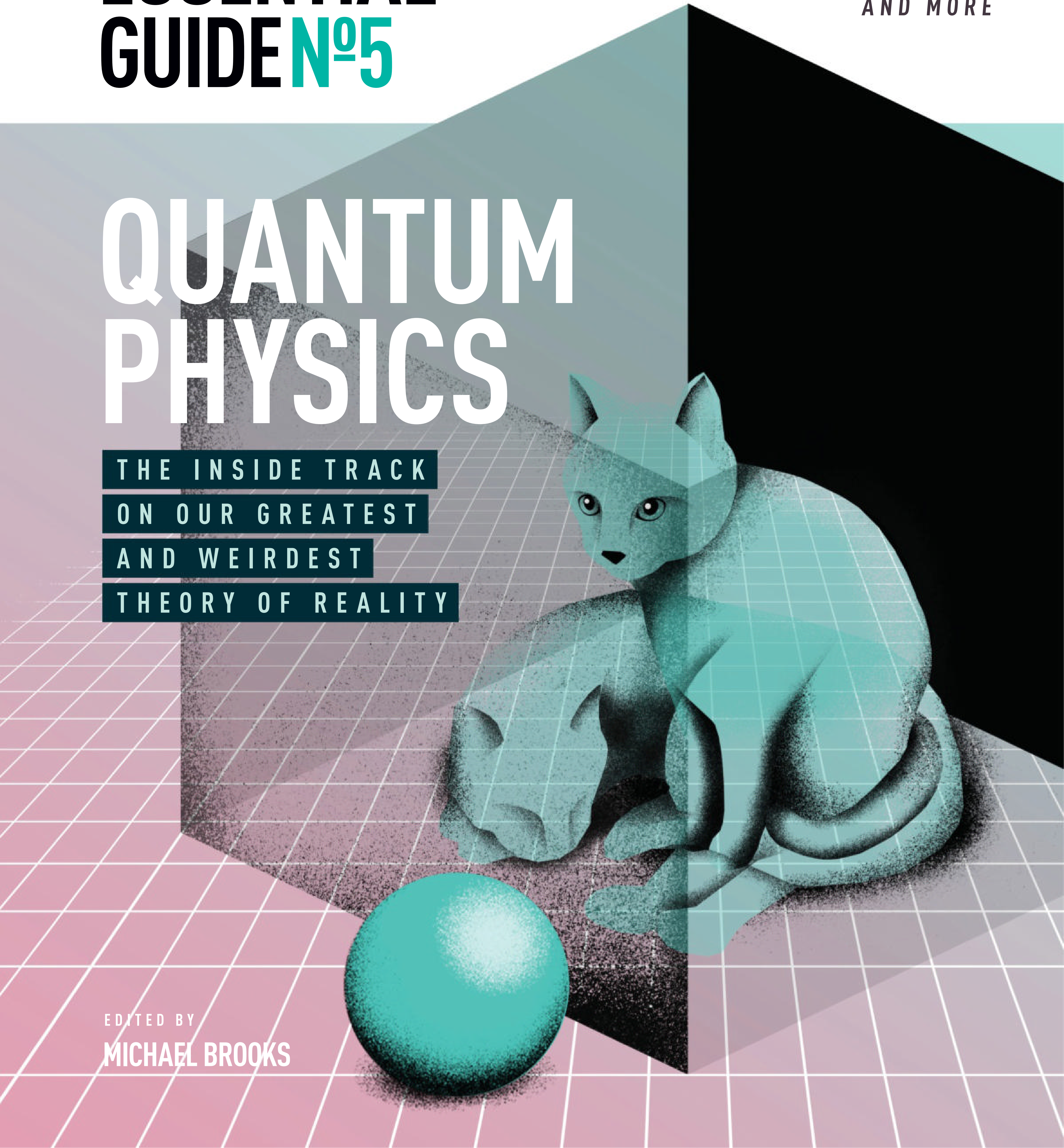
ORIGINS OF QUANTUM THEORY
HOW THE QUANTUM WORLD WORKS
QUANTUM TECHNOLOGIES
THE SEARCH FOR EVEN BETTER THEORIES
AND MORE

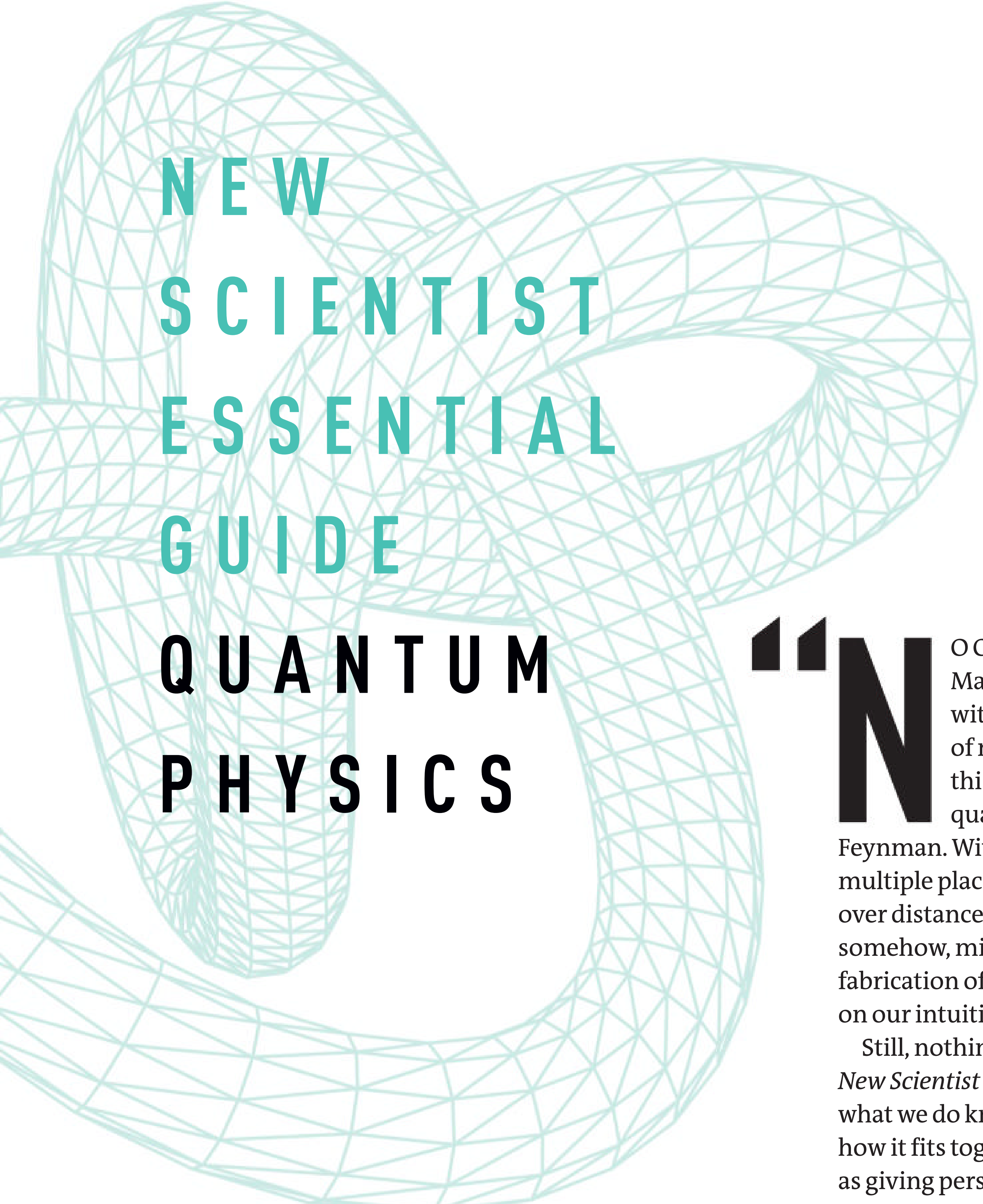
ESSENTIAL GUIDE Nº5



QUANTUM PHYSICS

THE INSIDE TRACK ON OUR GREATEST AND WEIRDEST THEORY OF REALITY

EDITED BY
MICHAEL BROOKS



NEW SCIENTIST ESSENTIAL GUIDE QUANTUM PHYSICS

"NO ONE understands quantum mechanics". Many who have attempted to get to grips with our most basic theory of the workings of material reality would nod vigorously at this quote from Nobel laureate (and quantum and particle physicist) Richard Feynman. With its dead-and-alive cats, particles in multiple places at once, spooky influences travelling over distances and strange implication that we all, somehow, might as observers be implicated in the fabrication of reality, the assaults of quantum theory on our intuition are legion, and legendary.

Still, nothing ventured, nothing gained. This fifth *New Scientist Essential Guide* aims to be a primer of what we do know: how quantum theory came to be, how it fits together and the problems it presents, as well as giving perspectives on technological advances it is bringing in the realms of quantum computing, and what better theories might lie beyond quantum theory.

I hope you find it a stimulating read; feedback is welcome at essentialguides@newscientist.com. Just remember, if you don't arrive at a full understanding of quantum physics over these 96 pages, at least you're in very good company. *Michael Brooks*

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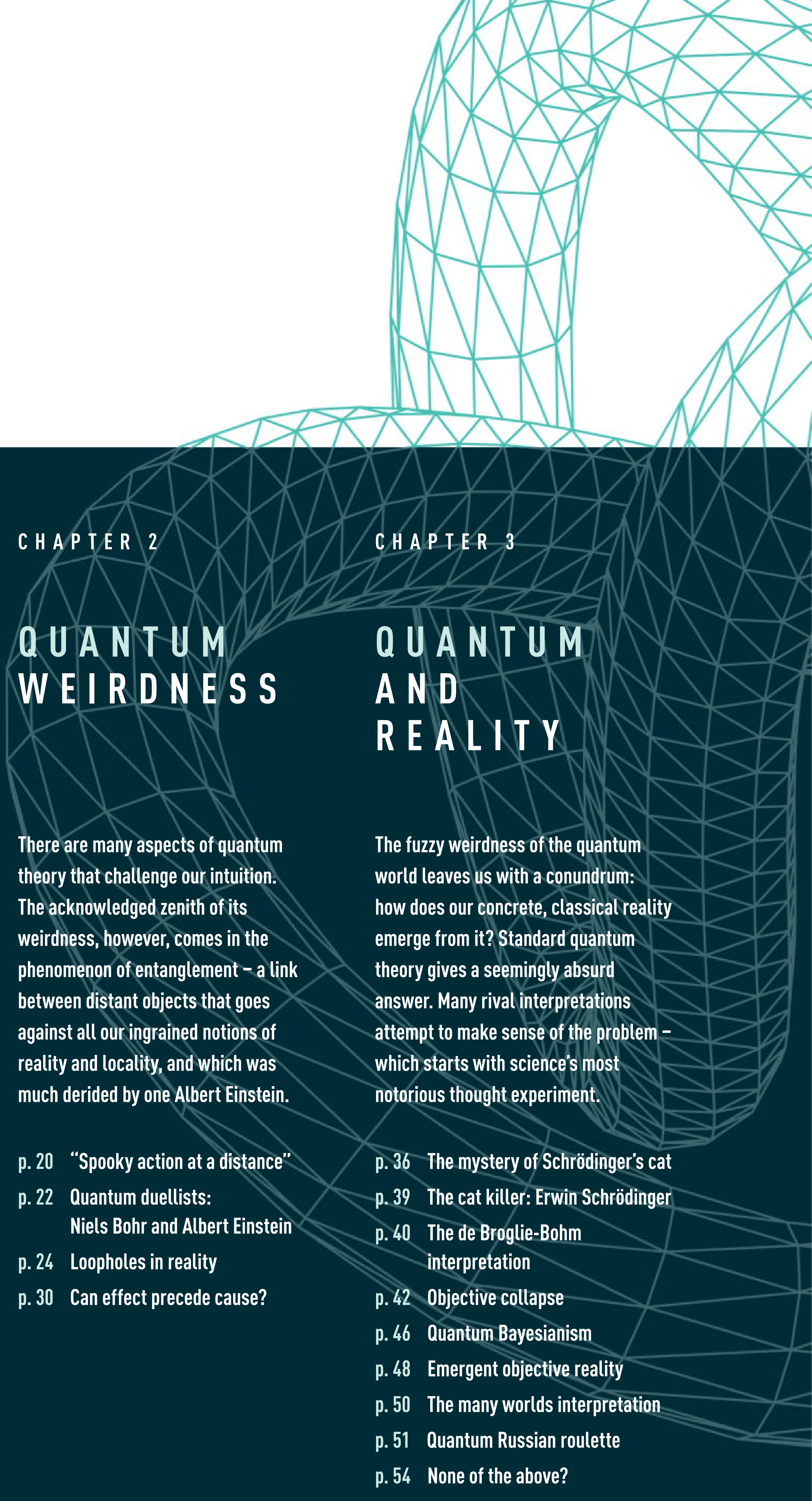

CHAPTER 1

INTO THE QUANTUM WORLD

Quantum theory is perhaps the most rigorously tested theory in all of science – and yet its random nature and prediction of weird, probabilistic effects and spooky influences challenges our intuitions about how reality should work. So how did the theory come to be, and what does it tell us?

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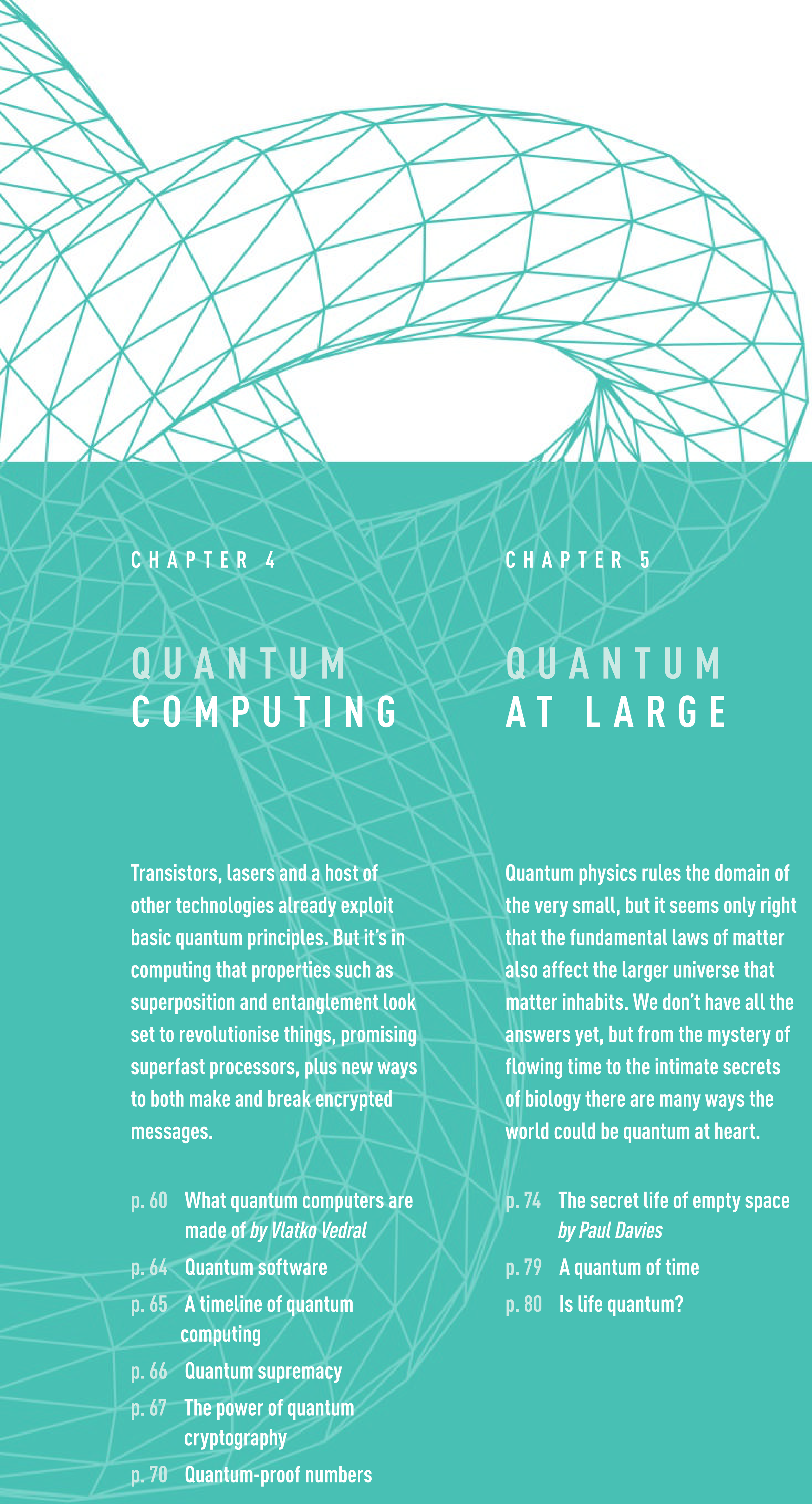

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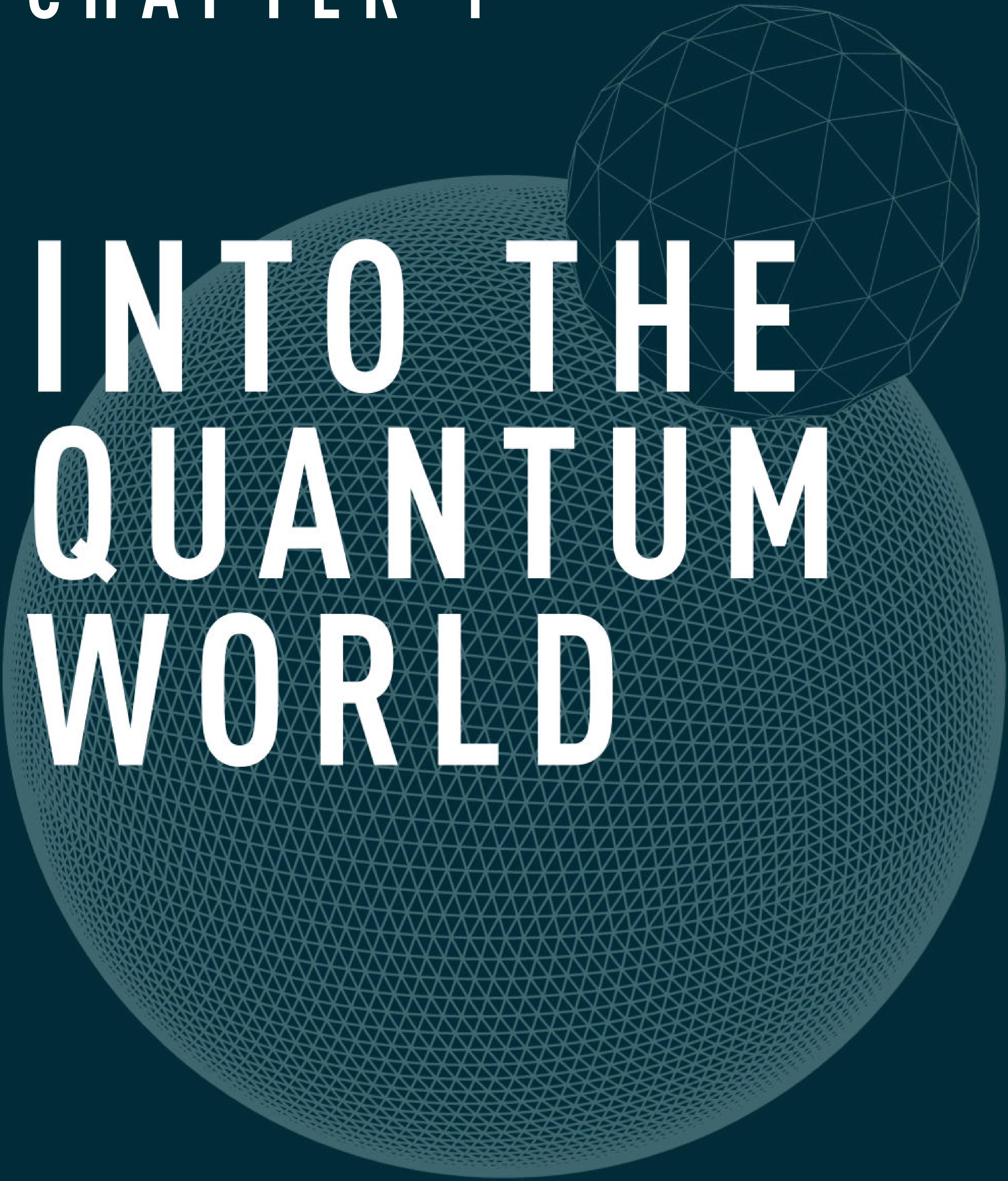
CHAPTER 1

INTO THE QUANTUM WORLD



Quantum theory is perhaps the most rigorously tested theory in the history of science. It is the fundamental theory of subatomic particles and their interactions, and the basis of models of how three of the four forces of nature work, gravity excluded.

It has never yet delivered a wrong result – and yet quantum theory's random nature and prediction of weird, probabilistic effects and spooky influences between objects that don't seem to be in contact challenges our intuitions about how reality should work. Let our journey into this strange realm begin.

THE ORIGINS OF QUANTUM MECHANICS

In 1894, physicist Max Planck was warming to a new challenge. A consortium of electric companies had commissioned Planck to make a light-bulb filament generate maximum light for the least amount of energy. It was a mundane start to perhaps the most extraordinary voyage of intellectual discovery science has ever taken us on.

MAX PLANCK'S light-bulb calculations swiftly encountered a problem. The physics he knew predicted that a heated object should absorb and emit electromagnetic radiation at all frequencies, meaning it should generate infinite amounts of energy. Experimental data, not to mention common sense, suggested otherwise.

It took Planck a few years before he had his own light-bulb moment: if energy is absorbed or emitted in discrete packets, then the energy radiated by a heated object would be finite. The theory seemed absurd at the time, but once physicists started looking, these "quanta" popped up all over the place. As quantum theory developed, it became clear that not just energy, but many other properties such as electric charge and spin – a property itself only discovered once quantum theory was applied to the electron – come in units of a minimum size. Why that should be, no one knew.

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MARIO WAGNER

Planck initially thought these quanta were a limitation of the theory, not a description of reality. But in 1905, Albert Einstein showed that the way some metals expel electrons when light shines on them – the photoelectric effect – could also be explained by assuming that light is made of discrete particle-like quanta, which he called photons.

Einstein's idea flew in the face of hundreds of experiments showing that light was like a ripple spreading on a lake or pond. The only plausible explanation was that somehow light must be both a wave and a stream of particles. In 1923, French physicist Louis de Broglie took this idea and ran with it, proposing that, just as light waves could behave like particles, the fundamental particles of matter could behave like waves. This, perhaps the most fundamental statement of quantum theory, is known as wave-particle duality.

De Broglie imagined an electron as a "matter wave" rippling through space. But as the idea was fleshed out mathematically, that interpretation was quietly dropped. It later became revived as part of the de Broglie-Bohm interpretation, one way to get around the quasi-philosophical problems that quantum theory would present. The consensus became and remains, however, that the waves associated with quantum particles were totally abstract things, unlike any waves anyone has ever seen or had ever imagined.

→
See chapter 3 for more on interpretations of quantum theory

All waves can be described mathematically – a ripple across a pond, for example, is a disturbance in water; its "wave function" describes its shape at any point and time, while something called the wave equation predicts how the ripple moves. Dealing with this required a whole new, highly abstract brand of mathematics developed by Werner Heisenberg and others – quantum mechanics.

The Austrian physicist Erwin Schrödinger realised from de Broglie's work that actually every quantum system – photon of light, matter particle, whatever – has a wave function associated with it, though he struggled to explain what the disturbance would be in the case of an atom or an electron. Nevertheless, he used this insight to develop the equation bearing his name that describes how wave functions – and thereby the particles that are the basis of matter and concrete, classical reality – evolve in time.

This work led to a radical new picture of the reality underlying the world. Schrödinger's wave equation encodes all the possible behaviours for a quantum system, but with certainties giving way to probabilities. Picture the simple case of an atom flying through space. If you know its wave function, you can use Schrödinger's equation to work out the probability of finding the atom at any location you please. But you can't tell where it is without measuring it. If you were to measure an identical particle again in exactly the same way, you would quite possibly find it somewhere different, according to the probabilities of different positions encoded in the wave function.

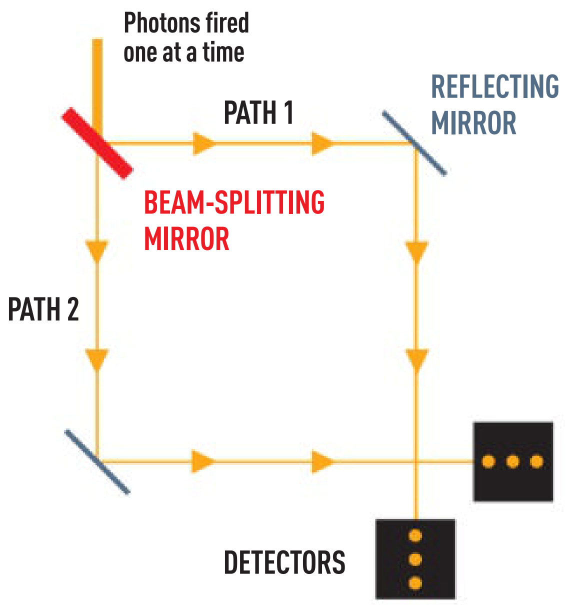
The mathematics works – we've never encountered any experimental result that contradicts its predictions. That is good enough for most physicists, who believe the wave function to be merely a probability distribution – a statistical summary of what large numbers of measurements would tell you about the properties of the particle.

Yet many physicists have found the

Using an interferometer to measure single photons in two different ways illustrates two key weird properties of quantum theory – randomness and spooky action at a distance

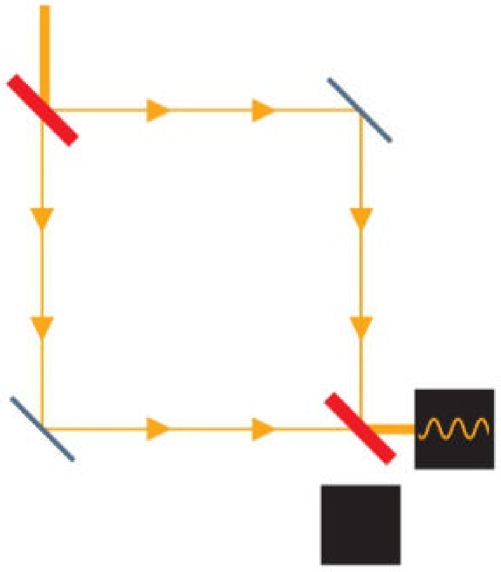
RANDOMNESS

Measuring each path separately produces blips split between two detectors at random – and you can never tell which will fire



SPOOKY ACTION AT A DISTANCE

Measuring the paths after they are combined again at a second mirror produces a wave-like interference effect with all hits on one detector, as if a single photon has taken both possible paths



consequences of wave-particle duality, and the probabilistic picture of reality it spawned, hard to swallow. In the famous words of Einstein, who became an arch-sceptic of quantum theory, "God doesn't play dice with the universe".

A very simple experiment illustrates the problems. First, imagine sending a single photon of light through a beam splitter, a piece of glass that either reflects it or transmits it with a 50 per cent chance. One of two detectors clicks in each of the two cases.If we run this experiment many times, we find that half of the time detector 1 clicks, and the other half detector 2.

But quantum mechanics shows that nothing in the universe can tell us which detector will click any one time. Einstein came from a classical frame of mind where everything is deterministic and predictable. The lesson of this experiment, however, seems to be that randomness really is at the heart of quantum mechanics.

But suppose now, instead of detecting the photon with two detectors behind the first beam splitter, you first recombine the light at a second beam splitter, with two detectors now behind here. What's remarkable now is that the photon behaves perfectly deterministically. Basically, only detector 1 clicks, never detector 2 (see diagram, left).

How can two random things be put together to give you something 100 per cent predictable? In quantum mechanics, the only way to explain it is to say that the photon actually splits into two at the first beam splitter and takes both routes: it's reflected and transmitted simultaneously. When these two possibilities converge on to the second beam splitter, they interfere like water waves: when they go to detector 1, they amplify each other, and when they go to detector 2, they cancel out and make no signal.

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There's more on similar "double slit" experiments on page 13 later in the chapter

We call this state of the photon a quantum superposition – it looks as though the photon can exist in two places. We've tested the effect not just on photons, but also on atoms, subatomic particles and larger particles and molecules, and every time we've actually got them to behave this way.

It gets even weirder: the phenomenon of entanglement suggests quantum particles that were once in contact retain a spooky link throughout their lives, however far apart they may drift. That was the source of another Einstein zinger, when he did that phenomenon down as "spooky action at a distance".

→
Chapter 2 has more on weirdness and entanglement

But he had a point: all this weirdness has serious consequences. If you accept quantum physics at face value, then at least one of two dearly held principles from the classical world must give. Wave-particle duality and superposition assault the principle of "realism" – that the components of reality exist in a concrete, well-defined form at all times, and that they exist without you measuring them. Entanglement appears to undermine "locality", the idea that nothing in the universe can influence anything else "instantaneously", and effects can only have causes next to them in space or time. You don't have to be Einstein to find that hard to swallow. ▮

QUANTUM UNCERTAINTY

The strange predictions swirling round the new quantum theory didn't stop with de Broglie's wave-particle duality. In 1927, another young researcher came up with a statement about the reality it depicted that more than any has come to define popular perceptions of the quantum world. It also, you might say, is the determining factor in material reality existing at all.

SOME middle-aged men have trains in their attics. Niels Bohr had Werner Heisenberg. In the winter of 1926-1927, the brilliant young German was working as Bohr's chief assistant, billeted in a garret at the top of the great Dane's Copenhagen institute. After a day's work, Bohr would come up to Heisenberg's eyrie to chew the quantum fat. They often sat up late into the night, in intense debate over the meaning of the revolutionary quantum theory, then in its infancy.

One puzzle they pondered was that exposed by the trails of droplets left by electrons as they passed through cloud chambers, an apparatus used to track the movements of charged particles. When Heisenberg tried calculating these seemingly precise trajectories using the equations of quantum mechanics, he failed.

One evening in mid-February, Bohr had left town on a skiing trip, and Heisenberg had slipped out to catch some night air in the broad avenues of Faelled Park, behind the institute. As he walked, it came to him. The electron's track was not precise at all: if you looked closely, it consisted of a series of fuzzy dots. That revealed something fundamental about quantum theory.

Back in his attic, Heisenberg excitedly wrote his idea down in a letter to fellow physicist Wolfgang Pauli. The gist of it appeared in a paper a few weeks later: "The more precisely the position is determined, the less precisely the momentum is known in this instant, and vice versa."

To express that a little more precisely, what Heisenberg showed in his 1927 paper was that if you know a particle's position x to within a certain accuracy Δx, then the uncertainty Δp on its momentum p is given by the mathematical "inequality" $\Delta x \, \Delta p \geq \hbar/2$. Here, $\hbar$ is a fixed number of nature known as the reduced Planck constant. This inequality says that, taken together, Δx and Δp cannot undercut $\hbar/2$. So in general, the more we know about where a particle is (the smaller Δx is), the less we can know about where it is going (the larger Δp is), and vice versa.

It is a concept totally alien to our classically tuned way of thinking. If you kick a football, knowing where it is doesn't stop you knowing where it's going, within the limits of your senses. And yet it seems at a more fundamental level, that's just the way the world works.

The uncertainty principle also applies to other pairs of quantities such as energy and time, and the spins and polarisations of particles in various directions. As a statement of the fundamental unknowability of the quantum world, it has stood firm for the best part of a century. Its profound implications are hard to overstate. Think of our classical, clockwork solar system. Given perfect knowledge of the current positions and movements of its planets and other bodies, we can predict their exact positions and movements any time in the future with almost perfect accuracy. In the quantum world, however, uncertainty does away with any such ideas of perfect knowledge revealed by measurement.

But the consequences of quantum uncertainty are even more profound. The energy-time uncertainty relation is the reason why quantum particles can pop out of the nothingness of a

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vacuum and disappear again.

As long as the energy, ΔE, they borrow to do that and the time, Δt, for which they hang around don't bust the uncertainty bound, the fuzzy logic of quantum mechanics remains satisfied. Quantum field theory marries this idea with the statement from Einstein's special theory of relativity famous as $E = mc^2$ – that energy and mass are interchangeable – to depict all particles of matter as "excitations" that arise in underlying fields.

→
See page 74 for more on the quantum vacuum

The British physicist Paul Dirac started the ball rolling in this direction in the late 1920s with his equation describing how relativistic electrons – and with it most other matter particles – behave.

That is the starting point of what, a half-century later, became today's "standard model" of particle physics. The product of many decades of theoretical work, also in the years since, the standard model has been meticulously confirmed by experiment. It covers the workings of three of the four forces of nature, describing the interactions of force-carrying boson particles with matter-making fermions.

Two quantum field theories lie at its heart. Quantum electrodynamics (QED) is the unified "electroweak" theory of electromagnetism and the weak nuclear force. Quantum chromodynamics (QCD) is the theory of the strong nuclear force. The crowning glory of the standard model came in 2012, with the discovery of the Higgs boson, predicted almost five decades earlier. But that all started with uncertainty. ▮

UNCERTAIN GENIUS

WERNER HEISENBERG
BORN WÜRZBURG, GERMANY
5 DECEMBER 1901
DIED MUNICH, GERMANY
1 FEBRUARY 1976

Just 25 when he came up with his eponymous principle, Heisenberg made other seminal contributions to the emerging quantum theory – indeed, he won the 1932 Nobel prize in physics "for the creation of quantum mechanics".

The following year, Adolf Hitler's Nazi regime came to power in Germany. He was investigated by the SS, who condemned him for supporting the "Jewish" theory of relativity. But the regime decided he was too useful to be silenced, and he later became a central figure in German efforts to build a nuclear bomb.

Heisenberg's own attitude towards these efforts remained equivocal, as shown in transcripts of conversations secretly recorded in 1945 when he and other German scientists were captured and interned at Farm Hall in England. Much speculation exists, for example, surrounding the purpose of a visit he made to his old supervisor Niels Bohr in Denmark in 1941, an event dramatised in British playwright Michael Frayn's Copenhagen in 1998. Bohr later escaped occupied Denmark to Sweden and eventually the US, where he worked on the Allied nuclear bomb project.

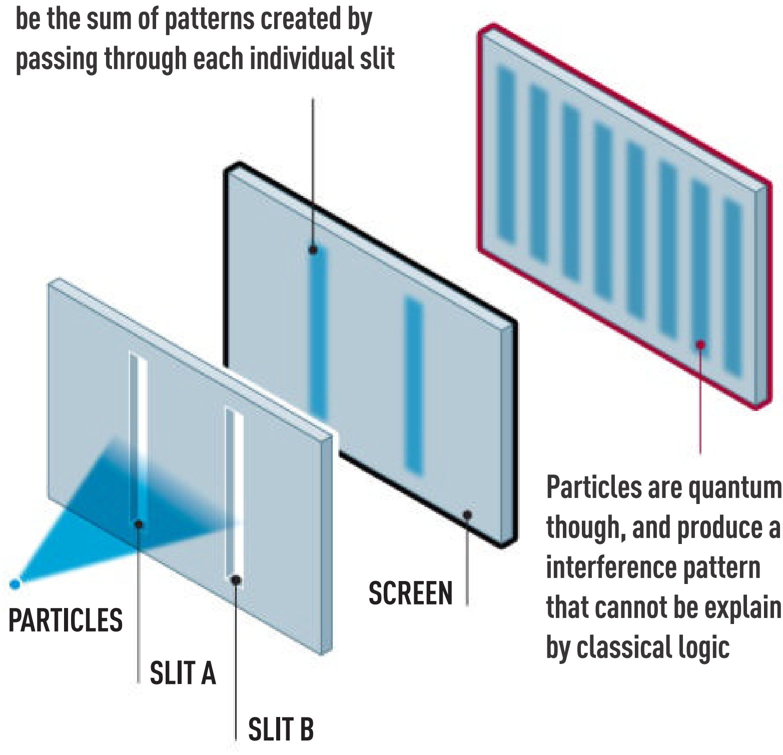
After the second world war Heisenberg returned to Germany and continued to work as a respected physicist, dying in 1976 at the age of 75.

THE EXPERIMENT THAT DEFIED REALITY

One experiment, in various iterations, did more than any other to establish that quantum theory's weird predictions do indeed reflect reality: the infamous double-slit experiment, which sends one thing two ways at once

The double-slit experiment illustrates the difference between quantum and classical mathematics

If particles behaved classically, the pattern they produce on a screen would be the sum of patterns created by passing through each individual slit



Particles are quantum, though, and produce an interference pattern that cannot be explained by classical logic

IN THE most basic version of the double-slit experiment, first performed in 1801 way before quantum theory came along, a beam of light illuminates a plate with two parallel slits cut into it. The light that passes through the slits hits a screen, creating stripes of light and darkness as a result of the interference between the two light waves that went through the slits. This interference is proof that light is not just a classical particle, as Isaac Newton had argued, but also a wave.

The weirdness of the quantum version is that interference happens even if you just send one photon through the double-slit set up. That is, it does if you measure the effects at a screen beyond the slits – then you measure a classical interference pattern, just as if the light were a wave. Measure at either of the slits, meanwhile, and you see a blip that indicates the photon passing through one slit or the other – a particle, in other words.

So, not only does a photon seemingly take two forms, but which form it takes seems to depend on how you measure it. "There's this magic-seeming thing that happens in quantum mechanics, which is that if there are multiple ways for an event to happen and you don't know which way it happened, you get quantum interference," says Alex Jones at the University of Bristol, UK. It is a result that physicist Richard Feynman described as embodying the "central mystery" of the quantum world.

If you find that mysterious, however, try the variant thought up by physicist John Wheeler in 1978. He found a way to delay choosing how to measure the photon effectively until after it must have "chosen" which

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slit to pass through. The effect, eventually verified in an experiment in 2007, is the same: measure at the slits and you see a photon, measure at a screen beyond and you see a wave.

The effect has since been verified with electrons, atoms and complex molecules – every object that is small and can reasonably be described as quantum exhibits the same behaviour.

But where does it end? If electrons can pop up in multiple places at once, why can't "classical" objects such as humans – essentially collections of fundamental particles – do the same?

This is where physicists invoke the wave function. When the particle is measured or disturbed in some way, its wave function collapses and it snaps into a single state and a definite position.

This collapse can be triggered by any interaction of a quantum object with its environment – a rogue vibration, for example, or a heat fluctuation. That leads us to an unsettling conclusion. Isolate a molecule even hundreds of thousands of times the size of an electron sufficiently from its environment, and there's a chance it might still be existing in its uncollapsed quantum state.

But there's a limit to how far you can practically take that. Since every moving particle can be considered as a wave, it also has a wavelength that, as determined by physicist Louis de Broglie, is found by dividing the Planck constant by the particle's momentum (which depends on its mass and velocity). You can think of the wavelength as roughly the scale at which the object's interactions with other things change from being classical and particle-like to quantum and wave-like.

If an object's wavelength is of a similar order to the size of the objects around it, the wave nature comes to the fore. The wavelength of a moving car, for example, is something around 10^{-38} metres, so on the road it behaves like a classical object. It would take some pretty tiny objects to expose the car's wavelike properties. Your own wavelength is similarly small, around 10^{-35} metres.

Not only does no one know how to fabricate a slit that fine, but "it's not even clear what space and time are doing on that scale," says Markus Arndt of the University of Vienna. And once you have worked out a way to fire someone at your grating, you have to stick them in a near-perfect vacuum and make sure they don't radiate any photons at wavelengths similar to the aperture size. The average person collides with about 10^{28} external bits of matter per second: enough to localise them. They also emit thermal photons.

Prevent all those interactions, though, and there is no reason, in principle, why you couldn't turn quantum. "Nothing in quantum theory puts any limit on the size," says Anton Zeilinger, also at Vienna. "Whether an object goes into superposition depends on the experimentalist. It's down to the choice of equipment."

As yet, no one has a definitive answer for how the photons switch between quantum and classical behaviour. "The interpretation question still remains with us," Zeilinger says. "I still find it mind-boggling." Yet he feels everything in the experiments fits with expectations. "The theory is a complete theory, and the experiments fit nicely with the theoretical idea." ∎

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A TIMELINE OF QUANTUM PHYSICS

Although its origins at the turn of the 20th century, a frenzied burst of discoveries in the mid 1920s really established the outline of quantum theory. Its application to the world of particles and forces has slowly developed in the decades since

1900 ↘

1900

MAX PLANCK INTRODUCES THE CONCEPT OF "QUANTA" OF LIGHT, BUT ONLY AS A THEORETICAL DEVICE

1905

ALBERT EINSTEIN EXPLAINS THE PHOTOELECTRIC EFFECT, THE EJECTION OF ELECTRONS FROM SOME METALS WHEN LIGHT SHINES ON THEM, BY POSITING THAT QUANTUM "PHOTONS" OF LIGHT ARE IN FACT REAL

1910 ↘

1913

NIELS BOHR INTRODUCES A QUANTUM MODEL OF ELECTRONS IN DISCRETE ORBITS AROUND THE ATOMIC NUCLEUS TO EXPLAIN THE SPECTRUM OF LIGHT THEY EMIT

1920 ↘

1922

THE STERN-GERLACH EXPERIMENT DEMONSTRATES THE EXISTENCE OF PARTICLE "SPIN", A NEW QUANTUM-MECHANICAL PROPERTY

1923

LOUIS DE BROGLIE FIRST POSTULATES THAT MATTER PARTICLES ARE ALSO WAVES, INTRODUCING A GENERAL CONCEPT OF WAVE-PARTICLE DUALITY

1924

WOLFGANG PAULI'S EXCLUSION PRINCIPLE USES QUANTUM THEORY TO EXPLAIN THE PERIODIC NATURE OF THE PERIODIC TABLE

1925

THE BIRTH OF QUANTUM MECHANICS AS WERNER HEISENBERG AND OTHERS DEVELOP THE MAIN "MATRIX MECHANICS" FORMULATION OF THE NEW THEORY

1926

ERWIN SCHRÖDINGER DEVELOPS HIS WAVE EQUATION THAT DESCRIBES THE EVOLUTION OF A QUANTUM OBJECT OVER TIME

1927

HEISENBERG FORMULATES HIS QUANTUM UNCERTAINTY PRINCIPLE

1927

BOHR AND HEISENBERG DEVELOP THE STANDARD "COPENHAGEN" INTERPRETATION OF THE NEW THEORY, WHICH SAYS THE WORLD IS FUNDAMENTALLY PROBABILISTIC, AND WE CAN'T FULLY KNOW ITS STATE BEFORE MEASURING IT

1930 ↘

1930
PAUL DIRAC MARRIES QUANTUM THEORY WITH EINSTEIN'S SPECIAL RELATIVITY TO DEVELOP A THEORY OF THE ELECTRON THAT ALSO PREDICTS THE EXISTENCE OF ANTIMATTER

1932
ANTIMATTER IS FOUND IN COSMIC RAYS – A TRIUMPH FOR QUANTUM THEORIES OF NATURE

1935
EINSTEIN, BORIS PODOLSKY, AND NATHAN ROSEN DEVISE THE EPR PARADOX WHICH INTRODUCES THE CONCEPT OF ENTANGLEMENT AND SAYS THAT QUANTUM MECHANICS CANNOT BE A COMPLETE THEORY OF REALITY

1935
SCHRÖDINGER DEVELOPS HIS INFAMOUS DEAD-AND-ALIVE CAT THOUGHT EXPERIMENT TO DEMONSTRATE THE APPARENT ABSURDITY OF QUANTUM THEORY

1940 ↘

1940s
BUILDING ON DIRAC'S WORK ON THE ELECTRON, A QUANTUM THEORY OF ELECTROMAGNETISM IS DEVELOPED, LATER UNIFIED WITH THE WEAK NUCLEAR FORCE

1970 ↘

1970s
A QUANTUM THEORY OF THE STRONG NUCLEAR FORCE IS DEVELOPED

1974
THE THEORIES OF THE STRONG FORCE AND THE ELECTROWEAK INTERACTION ARE COMBINED INTO THE "STANDARD MODEL" OF PARTICLE PHYSICS, OUR QUANTUM-BASED BASIC MODEL OF NATURE

2010 ↘

2012
THE HIGGS BOSON, THE LAST PREDICTED THEORY OF THE STANDARD MODEL, IS FOUND

2015
"LOOPHOLE-FREE" TESTS FINALLY PROVE THAT THE EPR PARADOX IS NO PARADOX – QUANTUM THEORY IS A COMPLETE THEORY

CHAPTER 2

QUANTUM WEIRDNESS

There are many aspects of quantum theory that challenge our intuition. The acknowledged zenith of its weirdness, however, comes in the phenomenon of entanglement.

Einstein thought that this strange link between quantum objects, which goes against all our conceptions of locality and causality, was proof the theory was lacking something. It seems on this one, Einstein was wrong.

“SPOOKY ACTION AT A DISTANCE”

Spukhafte Fernwirkung – that was the original German version of Einstein’s disparaging characterisation of quantum entanglement. In the end, though, it was those who thought it couldn’t be real who got spooked.

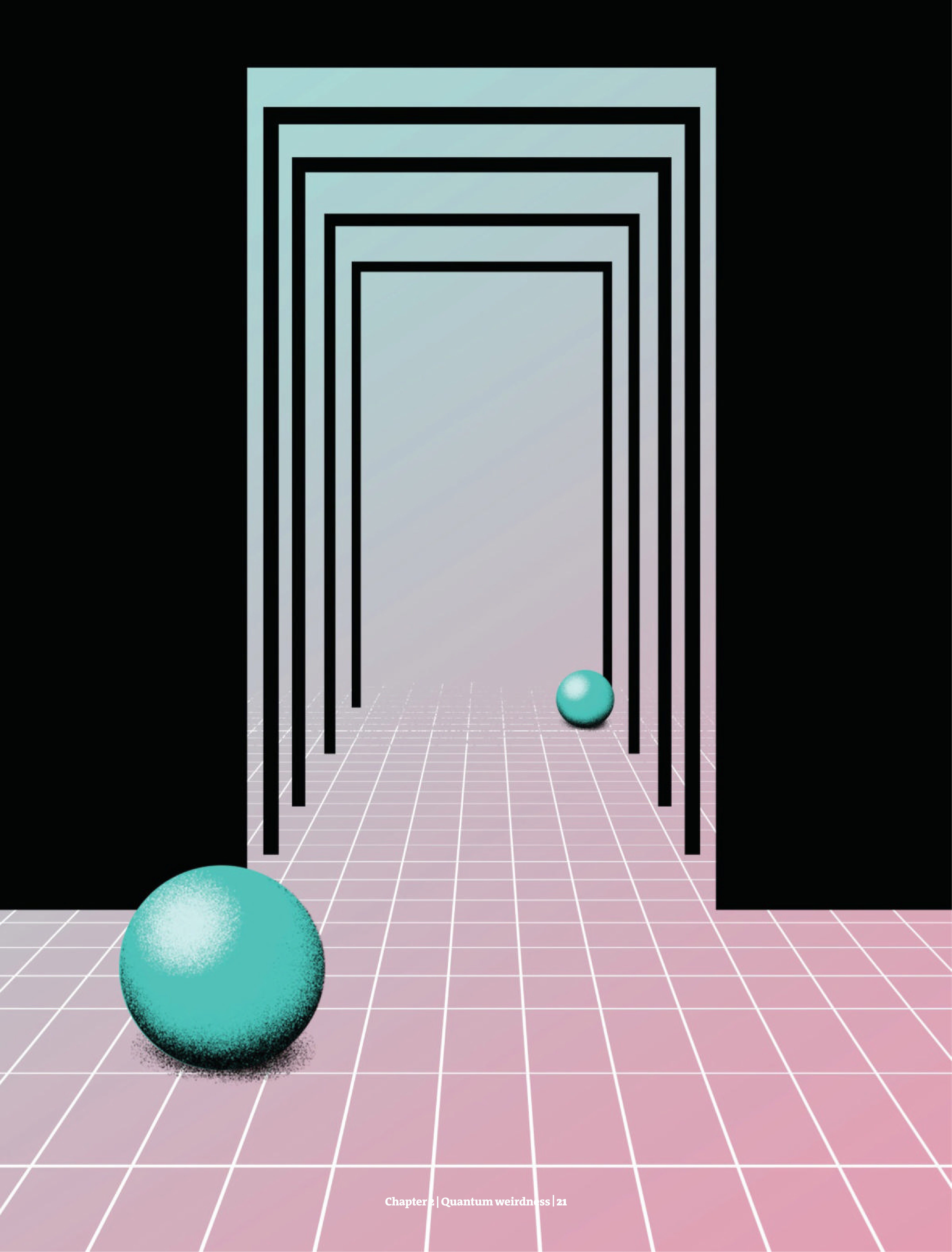
THROW a ball against a wall. Watch it bounce. Catch it. So far, so good. The ball didn’t suddenly disappear through a wall, or spontaneously turn into something else. This perfectly normal, predictable behaviour you just witnessed is classical physics in action. Up until 1900, it was just called physics. Whether you were discussing particles or planets, the rules that governed the bouncing of that ball could be used to describe anything in the universe. The world made sense.

Then quantum mechanics happened. The way it replaced hard certainties with wave functions and probabilities had some startling consequences. It meant, for example, that when faced with a hard barrier, a particle had a non-zero probability of being located on the other side, allowing it to perform the seemingly impossible feat of tunnelling straight through it.

←
Turn back to chapter 1 for more on the basics of quantum theory

Many physicists didn’t like this picture. Chief among them was Einstein, who was appalled at the consequences of the quantum world view he had helped usher in. To highlight the absurdity of this

MARIO WAGNER



radical new physics, he collaborated on a paper with two like-minded colleagues at Princeton University, Boris Podolsky and Nathan Rosen. Known as the EPR paper, after its authors, it laid out a troubling consequence of a universe governed by probabilities. Under the right conditions, EPR explained, two particles could have their wave functions tied together, or entangled, so intimately that any action you performed on one seemed to instantaneously influence the other – no matter how far apart they were.

This was heresy. In the language of classical physics, signals can only travel at the speed of light. This means that objects need more time to communicate with things further away from them than they do with ones in their immediate vicinity – a principle known as locality. Following that logic, classical physics says two entangled particles placed a light year apart would need a full 12 months to react to any change in one another. According to EPR, however, such reactions seemed to be instantaneous. Little wonder Einstein called the process "spooky action at a distance".

But not everybody got such a fright. Erwin Schrödinger embraced entanglement as the phenomenon that definitively separated the quantum and classical worlds, calling it the characteristic trait of quantum mechanics. To physicists such as Schrödinger, its very spookiness made it an ideal place to find the key ingredient that gave the quantum

QUANTUM DUELLISTS

The fight over the nature of quantum reality was fought, decorously and over many decades, between two great contemporaries – Niels Bohr, the helmsman of the "Copenhagen" school of researchers that dominated early quantum thinking, and arch quantum sceptic Albert Einstein

NIELS BOHR
BORN COPENHAGEN, DENMARK, 7 OCTOBER 1885
DIED COPENHAGEN, DENMARK, 18 NOVEMBER 1962

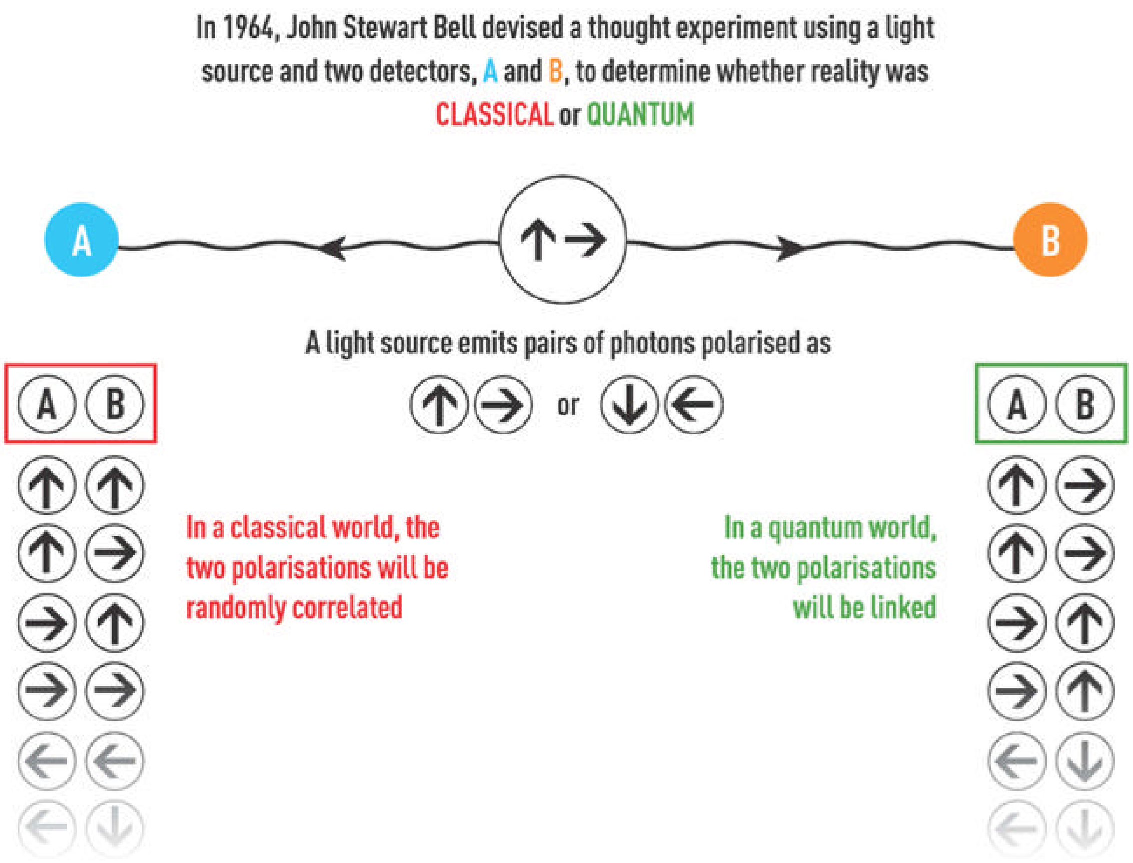
In 1913, Bohr used the principle of quantisation to postulate that electrons in atoms can exist only in discrete energy states, and thus explained the spectrum of light emitted by a hydrogen atom. This work ensured he followed Einstein to the Nobel prize for physics in 1922.

Bohr went on to develop the principle of complementarity, the bedrock of the dominant "Copenhagen" interpretation of quantum theory. This states that the quantum world is both wave- and particle-like; it is the act of measurement that causes it to show one face or the other.

ALBERT EINSTEIN
BORN ULM, GERMANY 14 MARCH 1879
DIED PRINCETON, NEW JERSEY, 18 APRIL 1955

In his annus mirabilis of 1905, Einstein not only came up with his special theory of relativity and the mass-energy equivalence equation $E = mc^2$, but also became the first person to ascribe a physical reality to the quantum, a concept introduced by Max Planck five years earlier.

Einstein described the liberation of electrons from an illuminated metal's surface – the photoelectric effect – in terms of the action of tiny, discrete packets of light energy: photons. It was for this insight that he received the Nobel prize for physics in 1921.


In 1964, John Stewart Bell devised a thought experiment using a light source and two detectors, A and B, to determine whether reality was CLASSICAL or QUANTUM
A
B
A light source emits pairs of photons polarised as
↑→ or ↓←
A B
In a classical world, the two polarisations will be randomly correlated
In a quantum world, the two polarisations will be linked
A B

world its quantumness.

Sceptics like Einstein were desperate to explain this bizarre twinning by purely classical means. One suggestion was that the two particles had predetermined properties that could be uncovered by means of observation. If you took a pair of gloves to opposite ends of the universe, for example, it would hardly be surprising to know that one glove was left-handed as soon as you identified the right-handedness of the other. The handedness of one glove didn't somehow emerge when the other was examined – it had been an integral part of its identity all along.

Such "hidden variables" theories, which appeared to explain entanglement while preserving locality, became the raft that quantum naysayers clung to with increasing desperation. That all changed in 1964, when physicist John Stewart Bell conceived a series of thought experiments that would be able to distinguish between true quantum entanglement and a classical equivalent that preserved locality (see diagram, above).

In a series of ever more accurate experimental implementations of his ideas from 1972 onwards, entanglement was shown to be a reality. Quantum physics was gleefully non-local. "These experiments sealed the fate on any hope of rescuing a crystal-clear picture of reality," says Matty Hoban, who works on quantum information theory at Goldsmiths, University of London.

But while non-locality is clearly an integral part of what makes quantum mechanics weird, it wasn't the end of the story. For one thing, non-locality only applies to two or more particles. It isn't present in any weird quantum effect involving a single particle, such as its ability to tunnel through walls or take multiple identities. Some other law of classical physics was also being broken.

The answer to this dilemma, once again, can be traced back to Einstein. Another assumption that EPR and its supporters had made was that quantum experiments obeyed similar rules to classical ones. They had assumed that any object had fixed properties, which could be uncovered by asking the right experimental question. A left-handed glove was always going to be left-handed: it was an intrinsic property that didn't vary. Whether you tested its handedness by putting it on, or asking a friend to put it on, or putting it on blindfolded while underwater, those different contexts shouldn't change its identity.

What Bell's tests had shown was that in the quantum world, they do have an effect. The result you got when measuring one of a pair of entangled particles was strongly linked to the measurement being made of its partner. In other words, each particle's answer must depend on the context in which it was being questioned. Viewed through that lens, all of the quantum world's most counter-intuitive results suddenly made sense. Possibly. ▮

LOOPHOLES IN REALITY

Entanglement is easy to define, but difficult to pin down. The inequalities derived by John Stewart Bell in 1964 provided a way of testing whether it was a real phenomenon, and so if quantum mechanics was "correct". At least they did in theory. Establishing the reality of Einstein's nemesis has pushed experimental physics to its limits – and pushed many physicists to theirs.

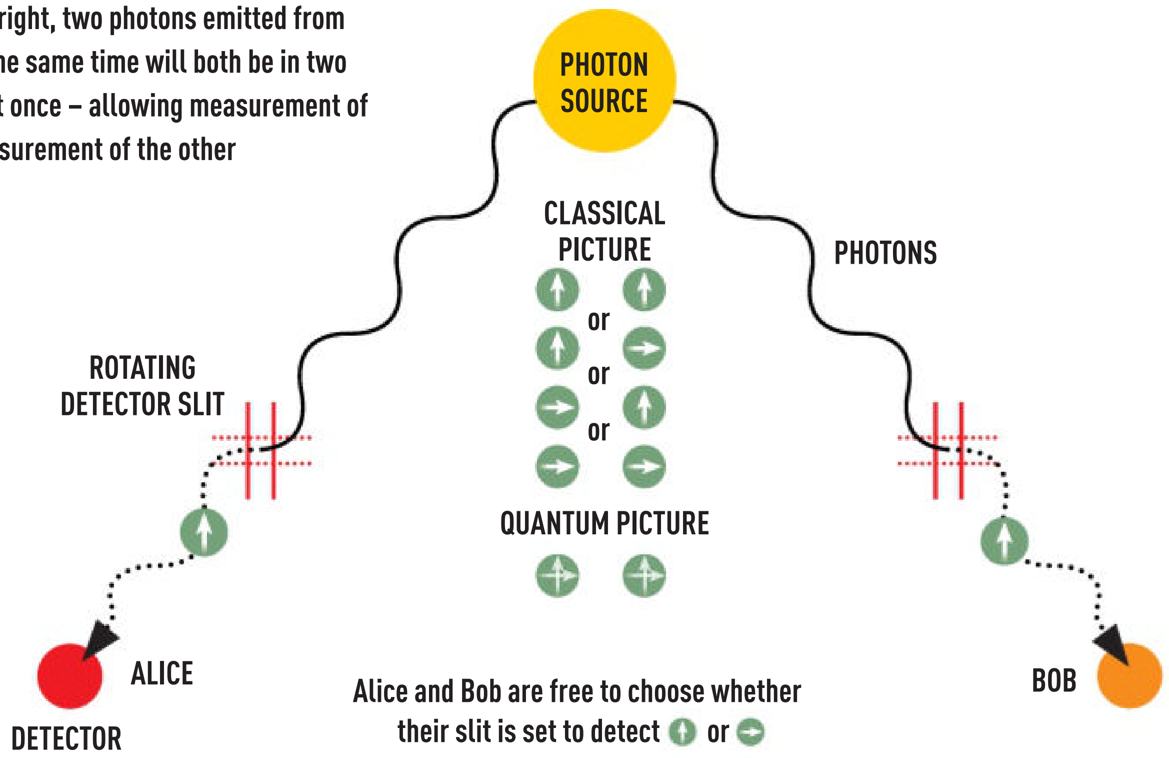
WHEN Rupert Ursin stood in the darkness at the highest point of La Palma in the Canary Islands he found it scary. "Really scary," he says. It was less the blackness stretching out towards the Atlantic Ocean some 15 kilometres away. It was more the sheer technical challenge ahead – and perhaps just a little because of the ghosts he was attempting to lay to rest.

Ursin and his colleagues from the Institute for Quantum Optics and Quantum Information in Vienna, Austria, were there that night to see if they could beam single photons of light to the 1-metre aperture of a telescope on the island of Tenerife, 144 kilometres away. Even on a fine day, when Teide, Tenerife's volcanic peak, is clearly visible from La Palma, that would be a feat of mind-boggling precision. Attempting it in the dark seemed ludicrous. "At night you don't know where the other island is," says Ursin. "You are lost; you have no clue what to do."

Such are the lengths physicists must go to in order to perform the sort of tests of quantum entanglement suggested by Bell. You first must produce pairs of quantum particles, such as photons, in such a way that from the viewpoint of quantum mechanics they are entangled. You then separate every photon from its companion in space, and independently measure a specific quantum property of each. For the most ambiguous possible test, you want photons that are as far apart as possible.

Most such tests look at polarisation, measured in one of two directions. In classical physics, you would expect there to be no correlation between outcomes of measurements on photons of a pair, beyond what you would get by random chance. In Bell's test, any theory that preserves both reality and locality would permit only a certain maximum amount of correlation.

If quantum theory is right, two photons emitted from the same source at the same time will both be in two polarisation states at once – allowing measurement of one to influence measurement of the other



Alice and Bob are free to choose whether their slit is set to detect ↑ or →

If they both choose the setting that lets only ↑ through, what is the probability that both, one of them or neither will register a photon?

CLASSICAL EXPECTATION

Alice	↑	↑	●	●
Bob	↑	●	↑	●
Probability	¼	¼	¼	¼

Alice and Bob's measurements are independent, so each combination is expected to be equally likely

EXPERIMENTAL REALITY

Alice	↑	↑	●	●
Bob	↑	●	↑	●
Probability	½	0	0	½

If Alice registers a hit, so does Bob and vice versa – evidence of SPOOKY ACTION AT A DISTANCE

Quantum mechanics, meanwhile, would allow the correlations to exceed this bound.

So if the correlations busted Bell's inequality by a significant amount, then realism, localism or both had failed, and the weirdness of quantum mechanics really did exist: the particles were in some mysterious way "entangled". If Bell's inequality was satisfied, however, then something real, local and classical-like was pulling the strings, something like the "hidden variables" that Einstein favoured.

It proved hard to implement the ideal conditions needed to test Bell's inequality. Then, in the early 1970s, a young French student named Alain Aspect came on the scene. He had just finished his mandatory military service as a teacher in Cameroon and was casting around for a PhD topic. Chancing upon Bell's paper and the history of the debate between Bohr and Einstein, he was entranced. "It was the most exciting thing for an experimentalist to test who was right," says Aspect, now at the Institute of Optics in Palaiseau, France.

So Aspect visited Bell to seek his blessing. Bell warned Aspect that many regarded investigating the roots of quantum reality as "crackpot physics", and asked him whether he had a secure job. "I did. It was small, but it was permanent," says Aspect. "They could not fire me." That security allowed Aspect to embark on a seven-year quest to test quantum physics to its limit.

Aspect's experiments broadly followed a pattern established in previous tests of Bell's inequality. Atoms were first stimulated to emit pairs of photons that were correlated in their polarisation states. These polarisations were then measured at two separate detectors, which are by convention maintained by two characters called Alice and Bob (see diagram, above).

That depended on measuring large numbers of photon pairs to get statistically significant results.

By the time Aspect, together with his students Philippe Grangier and Jean Dalibard, was ready to perform his definitive tests, advances in laser technology were making that an easier task. "By 1980, I had by far the best source of entangled photons in the world," says Aspect. Whereas it had previously taken hours or even days to get the number of photons required, he could now get them in just 1 minute.

It was still painstaking work. But by 1982 the researchers had the most convincing retort yet in the quantum reality debate. There was no doubting the results. Bohr was right; Bell's inequality was violated. The world is just as weird as quantum theory says it is. "It was thrilling," says Aspect.

End of story? Not a bit of it. Experiments are rarely entirely conclusive, and – influenced no doubt by Einstein's reputation – niggling doubts remained that perhaps nature had fooled the experimenters into thinking quantum theory was the true answer. Even if the measured correlations exceeded Bell's maximum, there were enough loopholes in the experiments to leave wiggle room for something other than quantum mechanics to be the cause.

"The question of whether nature is local, realistic or quantum-mechanical is so deep and so important that we should try to do these experiments as cleanly and as loophole-free as possible," says Johannes Kofler, a theorist with the Vienna team. "It's really all about ruling out conspiracy theories of nature against us."

Aspect's experiments had already done sterling work in trying to close one loophole that Bell had identified – the locality loophole. Unless the detectors used by Alice and Bob are far enough apart to prevent communication between them at light speed or below, some influence might propagate through a hidden layer of reality, telling Alice's detector the outcome of Bob's measurement before she performs her own, say, and maybe even fiddling with her detector's settings to change the outcome. "If you allow such a communication, it would be easy to violate Bell's inequality in local realism," says Kofler.

The highly efficient source of entangled photons and superior optics used by Aspect had enabled his team to separate Alice and Bob by about 6 metres. That gave them just enough time to change the settings of the detectors after the photons had left the source, hopefully stymieing any attempt of a hidden communication channel to ambush the experiment.

That was cunning, but not quite cunning enough. The team had only nanoseconds to change the detectors' settings, which was not enough time to change them randomly. Instead, they had to use a predictable, periodic pattern. If some hidden channel did exist, then over time the detectors used by Alice and Bob might figure out each other's settings and again trip up the experiment.

To nip that sort of thing in the bud, in 1998 Gregor Weihs, Anton Zeilinger and their colleagues strung Alice and Bob 400 metres apart over their university campus in Innsbruck, Austria, using optical fibres to connect the detectors to a photon source placed between the two. That gave them about 1.3 microseconds' grace after the photons were fired to switch the detector settings randomly. To close the locality loophole even tighter, atomic clocks ensured that Alice and Bob's measurements were made within 5 nanoseconds of each other – quick enough to prevent a hidden message being transferred. The test showed clear violations of Bell's inequality. Quantum mechanics reigned supreme.

And yet it still wasn't a final answer. As the locality loophole closed, attention shifted to other loopholes. One was the fair-sampling, or detection, loophole. The photon detectors used in all the experiments were inefficient and sampled only a small fraction of the photons sent out by the source. What if only a small subset of photons were sufficiently correlated to violate Bell's inequality, and the detectors just happened to be sampling those? Implausible, perhaps, but not impossible.

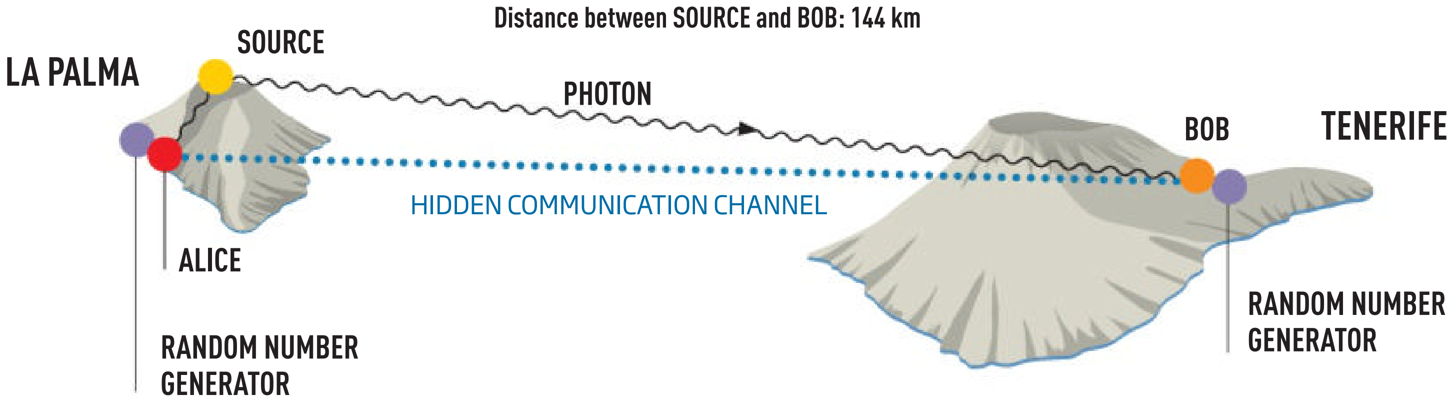
This loophole was first closed in 2001 by a group led by David Wineland at the National Institute of Standards and Technology in Boulder, Colorado. Instead of photons, the researchers entangled a pair of beryllium ions, each of which could exist in a quantum-mechanical superposition of two energy states. Depending on which state an ion was in, it scattered either very many or very few photons. By probing the ions with a laser and measuring the variation in photon counts, the ions' states could be determined with almost 100 per cent efficiency.

Again, the correlations found between the beryllium ions' states were far greater than could be explained by anything other than quantum mechanics. But this, too, came with a caveat: at the point of measurement, the ions were only 3 micrometres

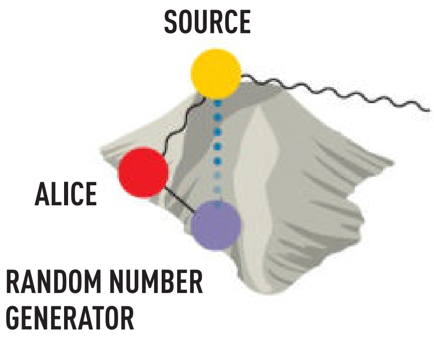
An experiment beaming photons between two Canary islands in 2011 aimed to close possible loopholes in experiments designed to show whether the quantum-mechanical property of entanglement, or spooky action at a distance, really exists

THE LOCALITY LOOPHOLE:
Light-speed "communication" through a hidden layer of reality might tell Bob's detector what Alice measured and change his settings accordingly

SOLUTION:
Keep the detectors far apart and use random number generators to change the detector settings while the photons are in flight



THE FREEDOM OF CHOICE LOOPHOLE:
The source of photons might tweak the settings of one or other of the detectors by influencing the random number generators



SOLUTION:
Put Alice's random number generator far away from the source, so no influence can pass between the two before the photon is detected

RESULT OF CLOSING THESE LOOPHOLES: ONE MEASUREMENT STILL SEEMS TO INFLUENCE THE OTHER

apart. Although the detection loophole was closed, the locality loophole remained open.

Besides, there was another subtle loophole to be considered. Tests of Bell's inequality generally assume that researchers have the freedom to choose their detectors' settings. But do they? What if the source of particles has some way of influencing the settings on the detectors used by Alice and Bob, again through some hidden layer of reality? By exploiting this "freedom of choice" loophole the source could emit photons that mimicked the entanglement of quantum mechanics.

That brings us to the Canary Islands. The aim of shooting photons from La Palma to Tenerife – an experiment combining the expertise of Ursin, Kofler, Zeilinger and others – was to close the freedom of choice loophole while also keeping the locality loophole tightly shut. While one entangled photon was beamed over the Atlantic to Bob in 479 microseconds, the other was pinged 6 kilometres down an optical fibre to Alice, reaching her in 29.6 microseconds. Random number generators triggered the detector settings for Alice and Bob once the photons were in transit (see diagram, above).

To ensure freedom of choice for Alice, her random number generator was kept 1.2 kilometres away from the photon source, and the random number generation and emission of photon pairs were timed so one could not influence the other. On Tenerife, the random number generator chose the setting for Bob's detector before the photon arrived from La Palma, ensuring that the source couldn't influence Bob's choice – assuming no influence travels faster than a photon.

The result? Yet again, the experiment violated Bell's inequality spectacularly.

With that, all three major loopholes – locality, fair-sampling and freedom of choice – had seemingly been closed. But in 2011, Michael Hall at the Australian ›

National University in Canberra had floated the idea that using random number generators might not be enough to close the freedom-of-choice loophole. If the random number generators and the photon source had interacted via a hidden mechanism any time in the past, that could have influenced the choice of measurement settings and maybe even the properties of the photons, creating the observed correlations. Hall's work eventually forced the experimentalists to think again. "I wanted to say to people: stop saying quantum mechanics is non-local as a matter of fact," he says.

But how could you exclude this possibility in an experiment? By outsourcing the random number generation to the universe itself.

Every event in space-time, such as Alice and Bob making a measurement, has a "past light cone": a volume of space-time from which a hidden influence moving at the speed of light or slower, can have travelled to affect it. So what you needed to do was ensure the random events used to choose the measurement settings were from as far back in the past as possible, excluding such meddlings.

That's where Andrew Friedman, Jason Gallicchio and David Kaiser had a brainwave. The idea was simple, but radical. Alice and Bob could use telescopes to receive photons from distant astronomical objects, and exploit each photon's colour to generate random digits for the measurement settings. For example, photons redder than some threshold wavelength could trigger a polarisation measurement in one direction, while bluer photons could trigger a measurement in the other. By using cosmological photons to determine the measurement settings, and demonstrating that the Bell bound was still broken, you could show that no hidden influence could have affected the detector settings in all the time the light was travelling towards Earth.

To do this, Kaiser, of the Massachussetts Institute of Technology, and his colleagues teamed up with Zeilinger's crew. Their first experiment placed the source of entangled photons on the rooftop of the institute on Boltzmanngasse in the city, and Alice and Bob in two buildings with a clear line of sight to the source: Bob on the fifth floor of the University of Natural Resources and Life Sciences roughly north, about 1150 metres away, and Alice on the ninth floor of the Austrian National Bank some 550 metres in a southerly direction.

Each night, once darkness set in, the team used small telescopes to observe stars in opposite directions in the sky. The photons collected by these telescopes were piped through optical fibres to special mirrors that sent them one way if the photon's wavelength was less than 700 nanometres, and another way otherwise, randomly generating 0s and 1s used to determine the measurement settings.

Like all others before it, the Vienna rooftop experiment broke Bell's bound, showing that any hidden influence could not be at work now, or in the past 600 years or so, the time the starlight had taken to reach Earth.

But the original proposal by Kaiser and his colleagues was more ambitious. It envisaged using light from very luminous galactic sources known as quasars, billions of light years away. "Quasars are the objects furthest away from us that are still visible with optical telescopes," says Scheidl. They were going to need a bigger telescope. It was time to climb a mountain once more.

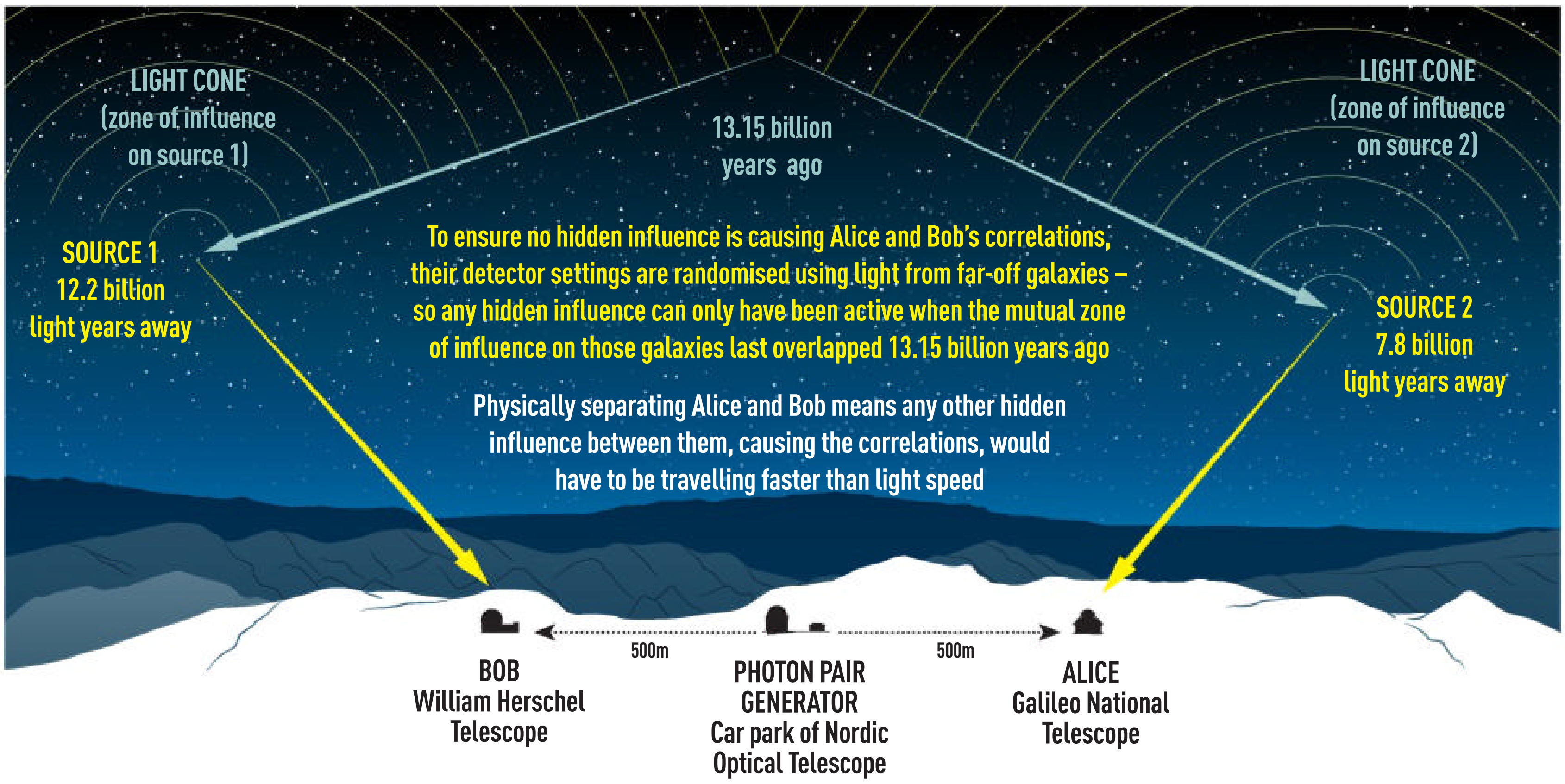
Just as in Vienna, the experiment required three sites, with Alice and Bob both hooked up to telescopes, a source of entangled photons in the middle, and a clear line of sight between the three. The Roque de los Muchachos, again, had the perfect configuration (see diagram, right). Alice could use photons from the Italian-run Galileo National Telescope, and Bob photons from the William Herschel Telescope, jointly funded by the Netherlands, Spain and the UK. Meanwhile, the car park for the Scandinavian-run Nordic Optical Telescope, situated almost exactly halfway between, roughly 500 metres from each, would house a container office with the optics to produce photons and beam them towards Alice and Bob.

It took a while to persuade the astronomers to give quantum physicists time on the two telescopes, but eventually three days of observing time were scheduled in December 2017 – with news that a team in China was doing a similar experiment setting the European competitive juices flowing.

The first night of observing was lost to a storm: it was hailing and the telescope dome couldn't be opened. Bad weather ruined the second of the allotted nights too. On the third night, things cleared up. With the moon below the horizon, and the sky dark except for the stars, the two large telescopes began tracking quasars.

But a problem with Alice's equipment meant she couldn't collect enough photons from her quasar – and before the team could fix it, telescope time was up. The next day, they went begging for more. The Galileo telescope was available, but at the other end it took the largesse of one Herschel astronomer, who gave up 2 hours of his allotted time to the quantum physicists. "We bought him some beer and wine," says Scheidl.

That night, the two telescopes locked into quasars in


LIGHT CONE
(zone of influence
on source 1)
13.15 billion
years ago
LIGHT CONE
(zone of influence
on source 2)
SOURCE 1
12.2 billion
light years away
To ensure no hidden influence is causing Alice and Bob's correlations, their detector settings are randomised using light from far-off galaxies – so any hidden influence can only have been active when the mutual zone of influence on those galaxies last overlapped 13.15 billion years ago
SOURCE 2
7.8 billion
light years away
Physically separating Alice and Bob means any other hidden influence between them, causing the correlations, would have to be travelling faster than light speed
500m
500m
BOB
William Herschel
Telescope
PHOTON PAIR
GENERATOR
Car park of Nordic
Optical Telescope
ALICE
Galileo National
Telescope

In the latest experiments atop the Roque de los Muchachos on La Palma in the Canary Islands, researchers have measured weird quantum correlations between pairs of generated photons – excluding the possibility the correlations could be explained by conventional physics

opposite patches of the sky to trigger the measurement settings for Alice and Bob. One had emitted its light 7.8 billion years ago and the other 12.2 billion years ago. The researchers were able to collect and analyse data for nearly 18,000 pairs of photons. Bell's bound was yet again broken, and strongly so.

Because the quasar sources are in different directions in the sky, their past light cones only overlap 13.15 billion light years in the past. That rules out any local-realistic mechanism pulling the strings from all but 4 per cent of the space-time it might have existed in – "virtually the entire past light cone of the experiment extending all the way to the big bang", says Kaiser.

The final word? Not quite. Even though the experiment closed the locality loophole and pushed the freedom-of-choice loophole to an extreme, "we were not even trying to close the fair sampling loophole", says Kaiser. The need to transmit the photons from the source to Alice and Bob through the air meant too many were lost to ensure watertight detection efficiency.

Meanwhile, the competing team in China, led by a former student of Zeilinger's, Jian-Wei Pan at the University of Science and Technology of China, made a stab at shutting all three loopholes. Losses of photons were minimised by using optical fibres to transmit them from the source to Alice and Bob, all situated on the outskirts of Shanghai. To generate the random numbers, the team used light from stars only 11 light years away, but still, "our experiment conclusively rules out local hidden variable models taking place 11 years before the experiment", says Pan.

Both teams are now thinking how to push things further, for example by using photons from the cosmic microwave background, the radiation left over from the big bang. "It'd be a delicious technical challenge, a really beautiful, really hard experiment," says Kaiser. "There is no earlier source of light in the cosmos that one could try to use."

Niggles aside, however, the conclusion already seems clear. It comes as little surprise to most physicists, but it's as well to check: Einstein's local-realistic universe, if it exists, has been pushed into a tiny corner of the cosmos. Elsewhere, there seems little room for doubt that quantum mechanics, or something based on it, is the correct description of nature. The theory's mysteries may remain as unfathomable as ever, but for Kaiser that is cause for celebration. "I think ordinary quantum theory looks as good as it ever has – which is to say, it looks terrific." ■

CAN EFFECT PRECEDE CAUSE?

If you were to break your arm tomorrow afternoon, would you suddenly find it hanging useless in a sling this morning? Of course not – the question makes no sense. Cause always precedes effect. But maybe life isn't quite so straightforward for a photon. In the quantum realm, the one thing that we always considered beyond the pale might just be true.

THE idea that the future can influence the present, and that the present can influence the past, is known as retrocausality. It has been around for a while without ever catching on – and for good reason, because we never see effects happen before their causes in everyday life. But a fresh twist on the entanglement conundrum suggests that we may have no choice but to think again.

No one is saying time travel is anything other than fantasy. But if the theorists going back to the future with retrocausality can make it stick, the implications would be almost as mind-boggling. They could not only explain the randomness seemingly inherent to the quantum world, but even remake the idea of entanglement in a way that finally brings it into line with Einstein's ideas of space and time – an achievement that has eluded physicists for decades. "If you allow retrocausality, it is possible to have a theory of reality that's more compatible with lots of things that we think should be true," says Matthew Leifer at Chapman University in Orange, California.

At issue is the way non-locality seems to fly in the face of Einstein's special theory of relativity, which states that no physical influence can travel faster than the speed of light. Whatever causes entanglement clearly does bust that bound. That contradiction is usually got around by saying there is no physical influence that causes entanglement; it is a facet of a

GETTY IMAGES

pre-existing link between the entangled particles.

Not everyone thinks that's good enough – certainly not the man who devised the tests that seem to indicate quantum theory, for all its non-locality, is the "right" theory of nature. "John Bell himself thought his work revealed a deep tension with special relativity," says Huw Price, a philosopher of physics at the University of Cambridge. "The appeal of retrocausality is that it removes that tension." By restoring a kind of locality, retrocausality also gives us the chance to rebuild quantum mechanics in a way that works with Einstein's theory of general relativity, the extension of the special theory that shows how gravity results from the warping of space-time by matter and energy.

"Most people have tried to recast gravity in quantum terms, but maybe it is the other way around," says Ken Wharton, a theorist at San Jose State University in California. "Maybe what we need to do is recast quantum theory in space and time. Retrocausality looks like one way to do that."

The notion that the present might influence the past in the quantum realm can be traced back to Paris in the late 1940s, when a young physicist called Olivier Costa de Beauregard spotted a way to explain pairs of entangled particles without invoking non-locality. Perhaps, he suggested, measuring one particle sent a signal back in time to the point in the past when the pair collided. The signal could then turn around and travel forwards in time with the other particle, ensuring its velocity was exactly in accordance with the measurement of the first one.

If a signal took this path, you could preserve locality without requiring the two entangled particles to have determined their velocities at the point of their collision. No instant communication, no violations of relativity.

At that point, no one had shown that non-locality was real. Only when Bell came along was there any reason to take de Beauregard's proposal seriously. But even then, with all manner of clever interpretations springing up to explain the perplexing results of the Bell experiments, retrocausality never really caught on.

It wasn't until 2010 that Price attempted to resuscitate the idea. His case revolved around a principle called time-reversal symmetry. This states that, mathematically speaking, the fundamental laws of physics work the same going backwards in time as they do going forwards. Of course, that doesn't tally with our everyday experience: you can't unscramble an egg, say, or unshatter a glass. (Physicists suspect that has something to do with the second law of thermodynamics, which says that entropy – the amount of disorder – always increases over time when large numbers of particles are involved.) But the fact is that fundamental physics is almost entirely indifferent to the direction of time. Nearly all physicists agree that most of the basic laws of physics obey time-reversal and they would be loath to give it up.

With that in mind, Price pointed out that if the laws of quantum physics obey time-reversal symmetry, as ›

“In the fuzzy quantum realm, the future really might influence the past”

they seem to, then retrocausality is inevitable. Yet there was a loophole in his argument. Price had assumed that the quantum description of a particle, known as the quantum state, corresponded to a real thing in the world, as opposed to being a mathematical tool for handling our own ignorance of said particle. For many, this was reason enough to ignore Price because the true status of the quantum state remains debatable.

But retrocausality is becoming harder to avoid. In 2017, Leifer and Matthew Pusey, now at the University of Oxford, found a way to close the loophole in Price’s argument. By merging Price’s ideas with Bell’s, Leifer and Pusey managed to show that retrocausality is necessary to save time-reversal symmetry regardless of whether the quantum state is real. This leaves another tricky choice: abandon time-reversal symmetry or embrace the idea that in the fuzzy quantum realm, the future really can influence the past.

Leifer is among those attempting to make good on the second option. The key might be a feature of relativity called the block universe.

In its marriage of space and time, Einstein’s great theory fatally undermines the concept of “now”. What is happening “now” in a particular location depends on where you are and how fast you’re moving, so two different observers may see different things at the same time in the exact same spot. This makes “now” an illusion. Time doesn’t really pass at all, and our perception that it does is due to our limited perspective on the world. In reality, past, present and future form a single, ever-existing block.

In a block universe, quantum retrocausality wouldn’t look so strange. If the past and the future coexist – if past events don’t fade away before future ones come into being – the future could easily influence the past.

What we need now, says Leifer, is a new version of quantum theory that incorporates the block universe to allow for retrocausality to emerge naturally. “The idea here is that you would formulate a theory of quantum physics over all of space-time, all at once,” he says, urging us to think of quantum cause and effect like a jigsaw puzzle. “When you do a jigsaw, you don’t do the bottom row first, and then the next. Each piece imposes constraints on the ones around it. So physics could be like that: each region of space-time could impose constraints on the neighbouring regions.”

But if the quantum world is a block universe shot through with retrocausality, why don’t we see retrocausality in our everyday lives? After all, we are all made of quantum stuff. The answer boils down to quantum uncertainty. Heisenberg’s uncertainty principle states that it is impossible to know both the position and momentum of a particle at the same time. So there are features of the quantum world that are persistently hidden from us, and this is ultimately what allows for retrocausation without letting us send signals to the past. “If my choice a minute from now determines one of these things that I don’t know, then I can’t send a signal back to myself,” says Wharton. “And yet it’s still retrocausal.”

Wharton is among those who argue that when you really think about it, retrocausality is no crazier than entanglement. And besides, he says, it brings plenty of advantages – not least the opportunity it affords physicists to remake quantum theory in a way that works with space-time. By restoring a form of locality, retrocausality might even lead to the long-sought explanation of how gravity manifests at the quantum scale.

“A lot of avenues have been left unexplored because people have been taught to think in this Newtonian picture of states evolving forwards," says theorist Emily Adlam at the University of Cambridge. "Retrocausality is going to open up many new possibilities that might hopefully get us out of the rut we're in."

It might also help to explain where the randomness in quantum physics that never sat right with Einstein comes from. According to Adlam, retrocausality suggests a neat solution: quantum randomness is an illusion that appears because we're only seeing part of the picture at any one time.

In that case, Einstein was in a sense right when he dismissed quantum theory's central premise with the words "God doesn't play dice with the universe". "God doesn't play dice, he plays sudoku," says Adlam. If you were doing a sudoku and you started on the left and moved towards the right, it would look as if you were seeing random events, she says. "But if you look at the whole thing at once... you can see all the rules, you can see that there's actually a unique deterministic solution from these global constraints to the whole grid."

Similarly, in a retrocausal version of quantum physics, what happens here and now could have effects on the distant past of a far-flung galaxy, effects that only make sense in the context of the "all-at-once" picture of the block universe. This may seem like a drastic departure from the ordinary laws of physics as we think of them, but to Adlam, that's not a problem. "It's quite naive of us to suppose that the laws of nature would take the form that is most convenient for us," she says. "To me, it's not in fact extreme or weird at all to go to this retrocausal picture."

Not everyone shares Adlam's enthusiasm. While it is true that time-reversal symmetry is a cherished property of nearly all the fundamental laws of physics, the version Leifer and Pusey use isn't the usual one. Rather than time-reversing the laws of physics themselves, they time-reversed the setup of their thought experiment, and showed that the results remained the same. This distinction gives sceptical physicists pause.

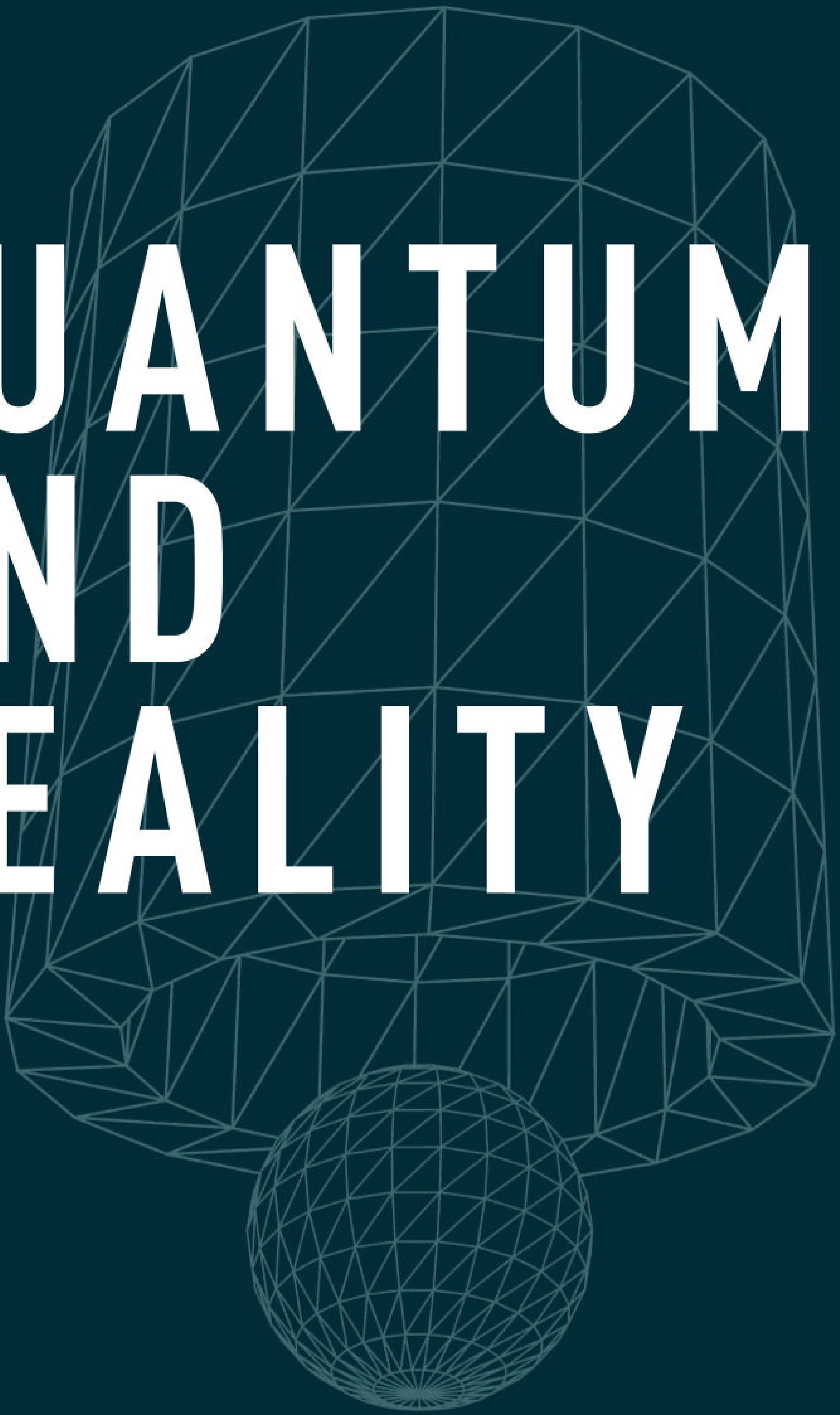
What's more, retrocausality doesn't answer every question facing quantum physics – at least not yet. "The next chapter in this story is just starting," says Wharton. The hard work begins now, he adds, as researchers attempt to develop a complete retrocausal theory, one that reproduces all the usual results of the hugely successful standard quantum theory.

But if recent work by Sally Shrapnel and Fabio Costa at the University of Queensland in Australia is anything to go by, even a fully retrocausal quantum theory wouldn't solve all the problems that niggle away at other interpretations of quantum physics. Although retrocausality handily accounts for the results of the Bell experiments, there is another issue, known as quantum contextuality, which may yet stop it in its tracks. Contextuality says that the outcomes of quantum experiments depend on what other experiments are conducted at the same time – a strange idea that physicists would prefer to be rid of. Now, Shrapnel and Costa have shown that retrocausality cannot easily dismiss it.

Although Shrapnel agrees with Leifer that retrocausality is worth investigating, she sounds a word of warning. "The retrocausal interpretation is not the free lunch that perhaps you might think it is," she says. "It's not going to be as simple as postulating backwards-in-time causal influences. We're going to need something even more exotic than that, and I think that's kind of cool." ■

CHAPTER 3

QUANTUM AND REALITY



"If you think you understand quantum mechanics, you haven't understood quantum mechanics." Nowhere does that jibe, supposedly made by physicist Richard Feynman half a century ago, ring truer than with the conundrum known as the quantum measurement problem.

This is the question of how our concrete, classical reality emerges from the fuzzy quantum world, and what role, if any, we play in that. Standard quantum theory gives seemingly absurd answers, so many rival interpretations have sprung up – all taking as their starting point science's most notorious thought experiment.

THE MYSTERY OF SCHRÖDINGER'S CAT

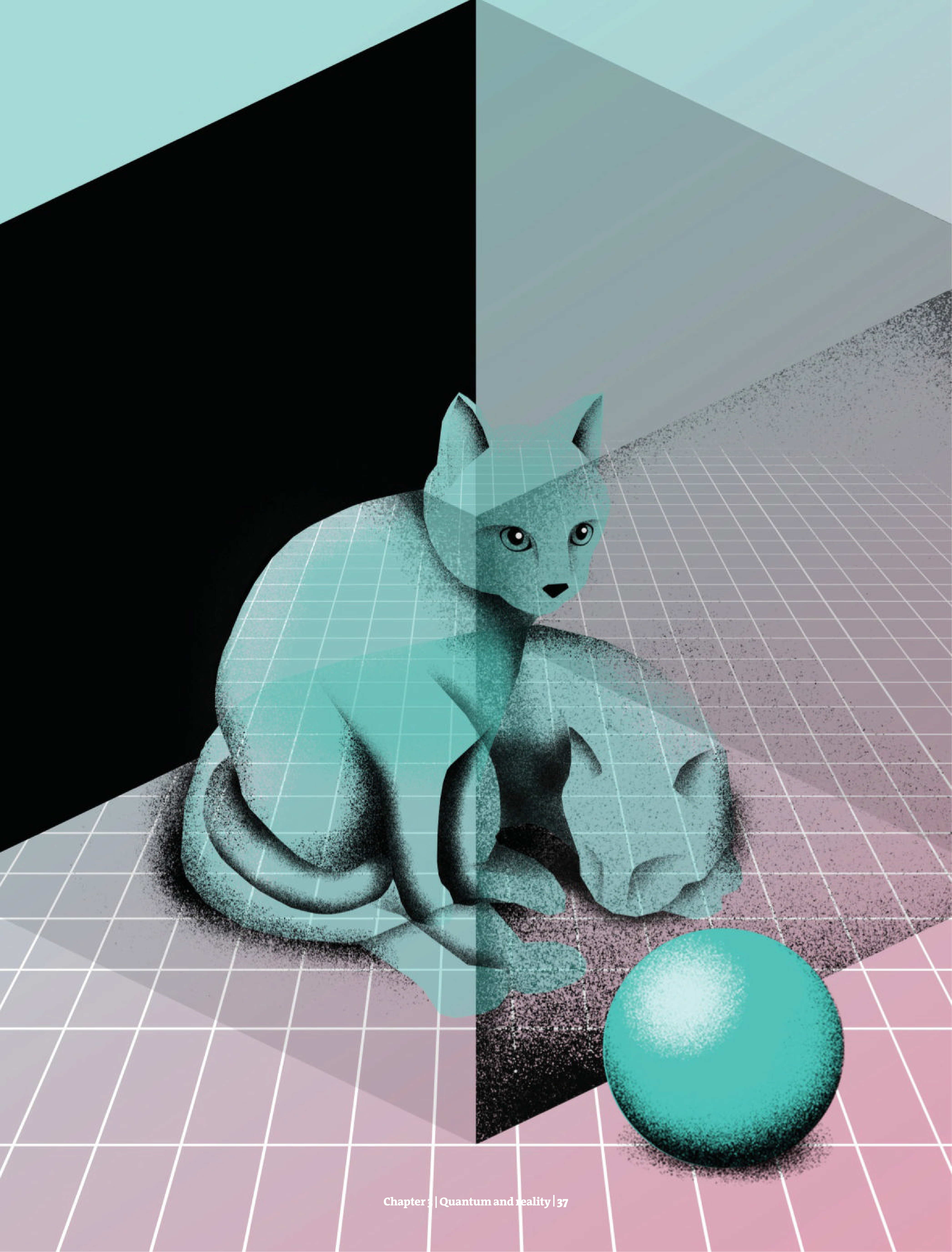
WANTED: DEAD AND ALIVE! When it comes to Schrödinger's cat, the hipster T-shirts write themselves. The zombie feline in an ambiguous state of animation fascinates the wider world. For quantum physicists, it is more of a tormentor, clawing at their belief in a treasured theory and coughing up hairballs over its claim to provide true enlightenment about the workings of reality.

EVER since its mathematical rules began to crystallise in the 1920s, quantum theory has been an affront to our sense of decency. In the world of things we can see and grasp, objects have robust properties that can be described by long-established, "classical" physical theories. In this realm, a cat has a binary position on the dead-alive scale. It also has a definite weight, fur colour, whisker length, position in space. You can measure these things at any time you like without the expectation of ambiguity or sudden change (except maybe in position: cats do sometimes move in mysterious ways). In a word, classical reality is what we would call real.

You wouldn't labour this point if, as we saw in the previous chapter, the quantum world weren't so different. An object that adheres to quantum rules doesn't have a reality that can be pinned down. Its properties are characterised by a probabilistic wave function that essentially says: if you make a measurement, here is what you might find.

Might – not will. Each time you measure a quantum object you "collapse" its wave function, causing the range of possible characteristics encoded in the maths to condense into a particular momentum or position, say (but not both, of course, because that would offend against the quantum uncertainty principle). But measure an object prepared in an identical way, and you are likely to find different values for those properties. Only by repeating identical ›

MARIO WAGNER



measurements can you gradually build up a sense of the object's overall reality, according to the probabilities encoded in the wave function.

So here's a question: what is that quantum object doing before you measure it? Does it have all those properties simultaneously? Or none of them? And when you measured it, forcing it to adopt a definite guise, what actually happened?

These conundrums lie at the heart of perhaps the most fundamental mystery in science, the quantum measurement problem. "The measurement problem has sometimes been called the reality problem," says theorist Lucien Hardy at the Perimeter Institute in Waterloo, Canada. "There's a kind of mismatch between our understanding about the way the world is and the picture a naive interpretation of the quantum state gives us."

That word "interpretation" is crucial because, from this point on, that is all we have: ideas or suppositions about what must be going on. The one with the fewest overheads is called the Copenhagen interpretation, devised in the Danish city by early luminaries of quantum physics such as Niels Bohr and Werner Heisenberg in the late 1920s.

A less august name for it is the "shut up and calculate" approach, because it essentially says that quantum theory isn't a description of physical reality itself, but just an operational framework that allows us to make predictions about it. "It's sort of a bit like a user interface," says Hardy. Fed with the right inputs, it predicts outcomes of measurements – but that is all. What reality is doing before those measurements is simply not a question quantum theory deals with.

Hardy himself isn't a fan of that interpretation. "It makes it hard to tell a consistent story," he says. Neither does it satisfy Nicolas Gisin at the University of Geneva in Switzerland. He knows his onions, having done pioneering experimental work exploiting quantum weirdness for real-world applications such as cryptography.

→
Chapter 5 has more on quantum computing and cryptography

"Practical physicists know what a measurement is, and they don't have to care too much," he says. "But if you want really to understand physics as providing a world view, you cannot accept that suddenly you have to say: forget everything, the measurement is just a kind of magical phenomenon that kind of comes on top of quantum and changes everything."

Such objections stretch way back. Albert Einstein pointedly asked if the anti-realism of the Copenhagen interpretation means the moon ceases to exist if we aren't looking at it. But it was Erwin Schrödinger who in 1935 gave the objections their T-shirt slogan-level public profile, with his wilful, if mercifully hypothetical, act of pet-related violence.

The scenario Schrödinger sketched was intended to illustrate the apparent absurdity of the interpretation. It places a flesh-and-blood cat in a box with a vial of poison that can be smashed – sending the moggie to meet its maker – by a mechanism that depends on whether a radioactive atom decays or not. According to the Copenhagen interpretation, the yes-or-no reality of this decay is undefined before you measure it. Ergo, so is the cat's reality. It too is in a quantum superposition of being both dead and alive.

For Schrödinger, this situation highlighted the absurdity of the "Copenhagen" interpretation, which permits things to be two ways at once until a measurement kills off the ambiguity (and possibly the cat). "He was trying to find a hyperbolic example that brought to light conceptual difficulties he was struggling with," says Robert Schoelkopf at Yale University.

But it appears to be a natural result of connecting the quantum and classical worlds. No theory dictates a boundary between them, and it is difficult to see where there could be one given that one world derives from

THE CAT KILLER

ERWIN SCHRÖDINGER
BORN VIENNA, AUSTRIA
12 AUGUST 1887
DIED VIENNA, AUSTRIA,
4 JANUARY 1961

Fated to be remembered only for his cat – thought to be inspired by a moggie called Milton he owned when a fellow of Magdalen College at the University of Oxford – Erwin Schrödinger worked out the basic dynamics of quantum theory in the mid-1920s, receiving the Nobel prize in physics in 1933 together with Paul Dirac for "the discovery of new productive forms of atomic theory".

That same year Schrödinger, a noted opponent of Nazism, had been forced to leave Germany. He eventually settled in Ireland, becoming a naturalised Irish citizen in 1948, where he furthered his eclectic research interests, including writing his famous book *What is Life?*, in which he attempted to apply the principles of physics to explaining living beings. He returned to his native Vienna in 1956, dying there a few years later.

the other. Quantum superposition states tend to be very delicate, which is one reason we have never put anything as large and lumpy as a cat in one. But we are working towards it. Real-world experiments have put ever-larger objects into quantum superpositions, even a tiny resonating metal strip visible to the naked eye.

←
Turn back to page 13 for more on double-slit quantum superposition experiments

Not that your naked eye will ever see that superposition directly, because looking at something counts as measuring it – making the cat either dead or alive.

Refinements of Schrödinger's thought experiment have only deepened the mystery. In the 1960s, mathematician and physicist Eugene Wigner painted himself into the picture as an additional observer. As his friend conducts a Schrödinger's cat experiment, Wigner stands outside the lab door. Before Wigner opens up and looks inside the lab, for him the friend-cat combination is in a quantum superposition of happy friend/live cat and sad friend/dead cat (presuming of course that Wigner's friend is a cat person).

This is so even if Wigner's friend long ago opened the box and ascertained what state the cat is in, and by extension their own emotional state. To compound the original measurement problem, quantum reality is now also observer-dependent. Different people can construe different versions of reality at any one time, with no way of saying which is right.

To spare blushes, Wigner proposed that the first conscious observation always collapses the wave function. But this just raises further questions. "What is an observer?" says Gisin. "I am an observer, presumably. Schrödinger's cat, maybe. Is a mosquito an observer? It's just not precise." And it is this imprecision at the heart of the measurement problem that leaves an awful lot up to interpretation – some of which we will look at now. ▮

THE DE BROGLIE-BOHM INTERPRETATION

The roots of one rival to the standard "Copenhagen" interpretation of quantum theory stretch back right to the beginnings of the theory – to that central mystery of wave-particle duality suggested by Louis de Broglie.

IN OCTOBER 1951, David Bohm left the US for Brazil. Branded a communist sympathiser, the physicist had been arrested for refusing to testify to the US Congress. Acquitted, he was still stripped of his Princeton professorship. His departure began an exile that would last until his death, as a naturalised British citizen, four decades later.

The theory Bohm was nurturing as he left his native shores has spent even longer in the cold. In part, that's down to politics. But his ideas were also scientifically beyond the pale. Bohm proposed there was a hidden reality to quantum theory, meaning its crazy predictions of a world that doesn't exist until you choose to look at it are just that: crazy. That went against the grain, and still does. But now, more than six decades on, Bohm is getting a fresh hearing, as new experiments hint he might have been on to something.

Louis de Broglie had presented his ideas about wave-particle duality at the 1927 Solvay Conference in Brussels, a legendary gathering of the early quantum greats. Central to his proposal was the idea that the wave side of the duality suggested the presence of a real, physically existing wave. But he had not developed the theory mathematically, and it received a lukewarm reception. He quietly dropped the idea, becoming an adherent of the Copenhagen interpretation.

Bohm was unaware of this work when, in the early 1950s, he developed a mathematically solid theory in which a wave with properties identical to that of the wave function guides particles around. "This wave is a pilot wave," says physicist Sheldon Goldstein of Rutgers University in New Jersey, "It choreographs the motion of the particles."

Bohm's theory made exactly the same predictions as standard quantum theory. But the fact that you could only predict outcomes of experiments probabilistically was because you lacked knowledge about the particles' initial state, not because nature doesn't exist when you're not looking. Bohm's ideas made de Broglie revisit and revise his own pilot-wave theory. He developed a two-wave theory in which every particle rides a pilot wave, which in turn interacts with another wave that behaves like a wave function.

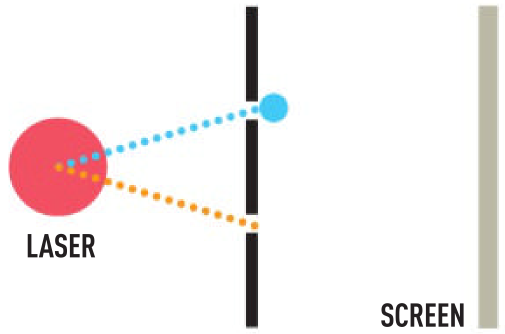
In another world, Bohm's work might have been seen as a breakthrough. But by the time the idea was published in 1952, he was already in exile. "A lot of the reception of Bohm's theory is tied up with that," says David Albert, a philosopher of physics at Columbia University in New York City. It didn't help that Einstein, then in his twilight years and a vocal critic of quantum theory, dismissed it too. In a letter to Max Born, another quantum pioneer, he wrote: "Bohm believes (as de Broglie did, by the way, 25 years ago) that he is able to interpret the quantum theory in deterministic terms… That seems too cheap to me." Bohmian mechanics entered the twilight zone of scientific theories – not quite dead, but not really a live concern either.

And there it has largely stayed. However, a refined version of the double-slit experiment (see page 13 for the classic version) conducted by Aephraim Steinberg of the University of Toronto, Canada, and his colleagues suggested that might not be such a problem. Brace yourself, because this is where things get really weird.

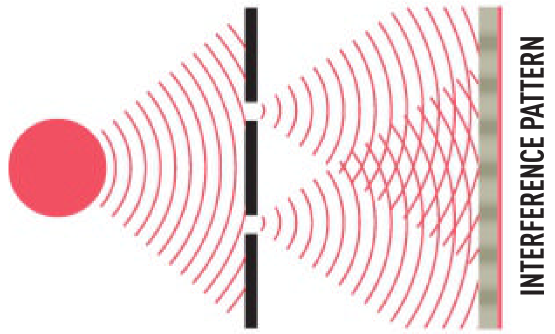
REALLY SURREAL

A twist on the classic quantum double-slit experiment deepens the mystery of reality

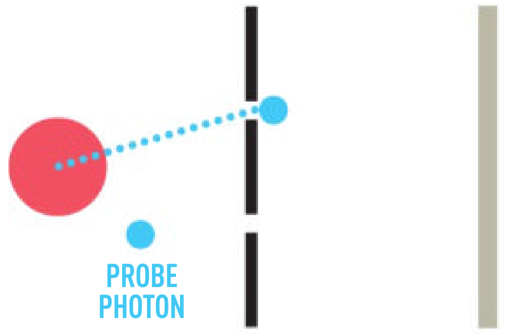
Measurements at the slits detect single photons passing through one slit or the other: LIGHT IS MADE OF PARTICLES



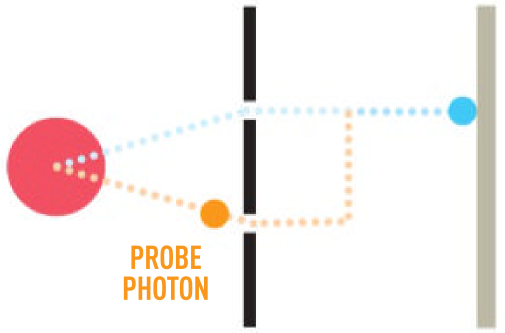
Allow the photons to reach the screen and an interference pattern develops over time: LIGHT IS A WAVE, and it passes through both slits



Now introduce an entangled "probe" photon that tells us which slit its partner photon passed through. Measure at the slits again, and the states of the two photons must agree



Take measurements at the screen, however, and half the time they disagree: the state of the probe suggests the travelling photon went through one slit, but its position on the screen implies it passed through the other – A SEEMINGLY SURREAL TRAJECTORY



First, the researchers created pairs of photons with entangled polarisations. One photon of each pair was sent through the double slit, which was designed so that if the photon was vertically polarised it would go through slit A, and if horizontally polarised through slit B. The second photon served as a probe: thanks to the entanglement, measuring its polarisation was akin to knowing the polarisation of the photon passing through the slits, and thus which slit it must have gone through.

This set-up (see diagram, left) gave the team two bites at the same cherry: they were able to determine the travelling photon's position as it went through the apparatus, and could also measure the polarisation state of the associated probe photon. They did this with tens of thousands of photon pairs, and found that, on average, at the moment a photon passed through slit A, the probe photon would be vertically polarised, as expected. But at the screen, things were a lot more ambiguous. When a travelling photon was measured at a position on the screen corresponding to having passed through slit A, half the time the polarisation of the probe photon was horizontal – suggesting that the travelling photon had passed through slit B. These were seemingly surreal trajectories, unmasked.

What's happening? In a word, non-locality. The experiment shows that the moving photon is constantly changing the polarisation of the probe photon. Look at the probe photon at the moment the moving photon goes through a slit, and there is no contradiction. But look at it the moment the moving photon hits the screen and, half of the time, its polarisation state has changed. This sort of non-locality is admissible in standard quantum theory, but it is baked into Bohm's version. The experiment is by no means a proof of Bohm's theory, but it shows that its prediction of surreal trajectories cannot be used to debunk it.

So Bohmian mechanics can and should remain a contender, says Albert. "Any realist picture is preferable to any anti-realist picture," he says.

But winning hearts and minds will still be a struggle. For a start, Bohmian mechanics is formulated to replicate the predictions of standard quantum mechanics: experimentally, it's almost impossible to tell them apart. Also, the theory is mathematically fleshed out only for particles travelling far slower than the speed of light. Quantum mechanics, in contrast, has been extended to embrace relativistic particles travelling close to the speed of light, and so forms the basis of quantum field theory and the standard model of particle physics. "Clean, worked-out Bohmian versions of those things do not exist," says Goldstein. ▮

If observing a quantum wave function collapses it, what happens when there are no observers? The absurdities that this question highlights leads some physicists to contend that wave function collapse must be an intrinsic property of the universe that observers just happen to accelerate. As a working hypothesis, this controversial idea has some distinct advantages.

OBJECTIVE COLLAPSE

WHERE, when you aren't looking at it, is a subatomic particle? A quantum physicist would probably answer: sort of all over the place. An unobserved particle is a wisp of reality, a shimmer of existence – there isn't a good metaphor for it, because it is vague both by definition and by nature. Until you do have a peek. Then it becomes a particle proper, it can be put into words, it is a thing with a place.

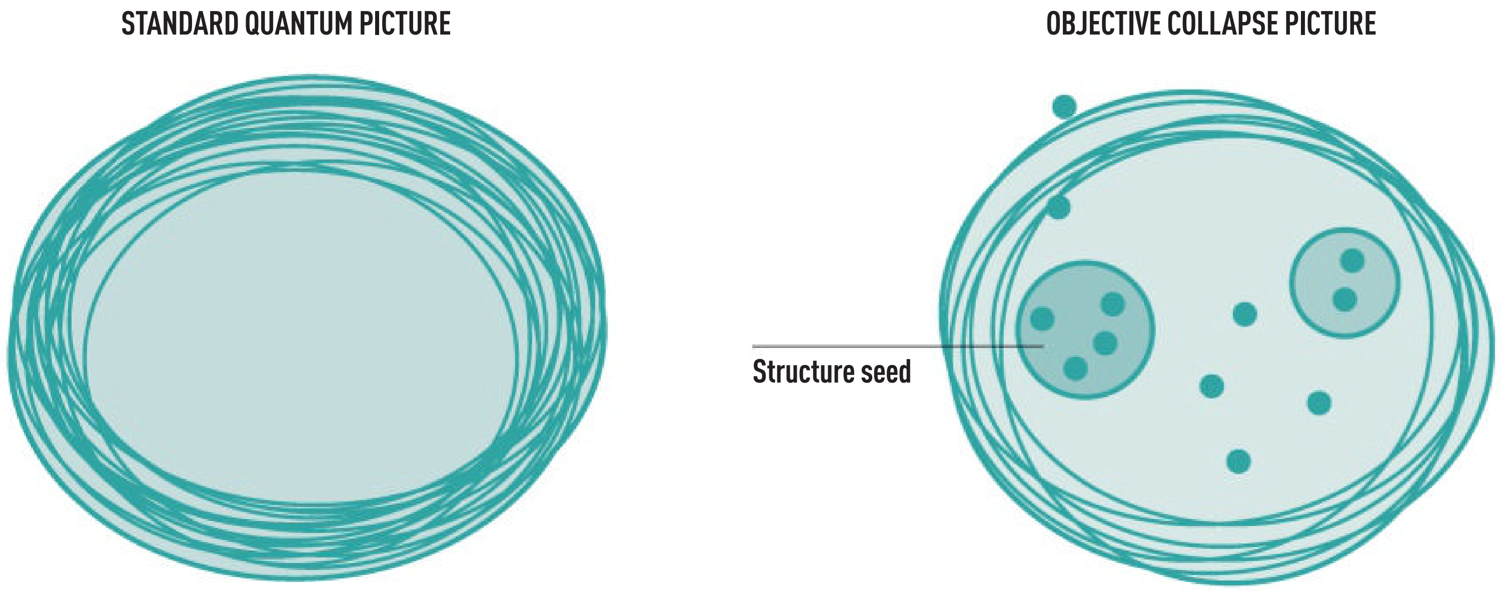
That picture seems utterly absurd. Einstein, in particular, was unimpressed, pointedly asking whether the moon is not there if no one is looking at it. But you could think even bigger: how did the universe come into existence if no one was there to observe it?

According to cosmologists, the early universe was a featureless blob, into which particles began to materialise at random. Particles that just happened to materialise closer together began to clump together through gravity – forming the seeds of today's stars and galaxies.

All well and good, except that there were no primordial observers to collapse the wave functions of those initial particles and create their uneven distributions in the first place. Believe the standard Copenhagen

HOW DID IT ALL BEGIN?

In our standard cosmological picture, the seeds of stars and galaxies were sown in the early universe by tiny quantum fluctuations in the density of matter. But standard quantum theory doesn't allow this



The locations of individual particles are uncertain. There's no observer to localise them to any one place - NO STRUCTURES FORM

Particles localise spontaneously, forming clusters that ultimately give rise to large-scale structures

interpretation of quantum theory, and the star-filled universe that we live in could never have existed.

We can resolve this with an interpretation where wave functions are real things and do indeed collapse – but randomly, by themselves. It doesn't need a human observer, so this process is known as an objective collapse. "Something like a measurement occurs, but without anybody actually measuring," says Daniel Sudarsky, a physicist at the National Autonomous University of Mexico (UNAM) in Mexico City.

Objective collapse would be rare, but catching. Wait for a single particle's wave function to collapse and you could be waiting longer than the age of the universe. Group many particles together, however, and the chance swiftly escalates. With a few billion particles, you might only have to wait a few seconds for one wave function to collapse – and for that to set the rest off.

Objective collapse theory was first put forward in the 1970s by Philip Pearle at Hamilton College in New York, and later refined by Giancarlo Ghirardi and Tulio Weber at the University of Trieste and Alberto Rimini at the University of Pavia, Italy. Their goal was to tweak Schrödinger's equation so that the wave function evolves naturally, without an observer, from a mix of states into a single, well-defined state. To do so, they added a couple of extra mathematical terms: a non-linear term, which rapidly promotes one state at the expense of others, and a stochastic term, which makes that happen at random.

At least superficially, these tweaks can explain quite a lot that's inexplicable about quantum theory. We never see ghostly quantum effects in large objects such as cats or the moon because, with so many interacting particles, their wave functions readily collapse or else never form. And in the early universe, as Sudarsky and physicist-philosopher Elias Okon, also at UNAM, showed a decade ago, it was only a matter of time before the wave functions of matter collapsed into an uneven distribution from which stars and galaxies could form.

Objective collapse theory has an intuitive explanation for the observer problem, too. The human body has upwards of one billion billion billion atoms, all of which contain yet more constituent particles. An observer meddling with even a carefully isolated quantum apparatus will inevitably become quantum-entangled with it, and their collapsed wave function then causes any uncollapsed wave function in the vicinity to collapse too.

The idea has been slow to catch on. For a start, it's only an "effective" theory. It states that wave functions collapse randomly and provides a mathematical description, but doesn't explain why. There are possible explanations – theorist Roger Penrose at the University of Oxford has suggested that gravity drives the process, for instance – but no consensus. The tweaked ›

> “Objective collapse might solve a whole load of cosmological problems too”

Schrödinger equation was also not relativistic; it did not work for particles moving at close to the speed of light, a basic requirement of any modern theory.

That began to change around 2011, when theorists including Daniel Bedingham of the University of Oxford and Roderich Tumulka of Rutgers University in New Jersey formulated the first relativistic objective collapse models. Still the idea had few takers. For Tumulka, that’s because persuading physicists to go for any option besides the standard Copenhagen interpretation is like Copernicus trying to persuade people in the 16th century to give up Ptolemy’s Earth-centric view of the universe. “The difference is that Ptolemy’s theory made perfect sense. It just happened not to be right,” he says. “But Copenhagen quantum mechanics is incoherent, and thus is not even a reasonable theory to begin with.”

More recent work might begin to turn the tide. It shows that objective collapse might explain not only how structure began to appear in the universe, but a host of other cosmological problems, too.

Take black holes. These monsters, created by Einstein’s theory of gravity, general relativity, crush everything that comes their way – light, matter, information. For around 40 years, physicists have been especially perplexed by the information bit. If all the information about a particle is contained within its wave function, and the only thing that can collapse a wave function is – according to the Copenhagen school, at least – an observer, who is that observer inside a black hole?

No problem in objective collapse theory: no observer is required. Sudarsky and Okon calculated that the rate of random wave function collapse given by their theory agrees with the information loss rate predicted for black holes.

Spontaneous wave function collapse makes stuff, too. When a wave function disappears, something new appears in its place – a definite position, a piece of information, a tick of energy. Each collapse can only generate a minuscule amount of energy, so we wouldn’t notice it on any everyday scale. But in the universe as a whole, this energy creation could be rather significant – and perhaps solve the biggest cosmological conundrum of all.

That conundrum is dark energy, the unknown entity that observations since the 1990s have indicated is accelerating the expansion of the universe. Standard quantum theory supplies what seems at first glance a ready source of dark energy. Quantum uncertainty means that even the nothing of free space has a small chance of containing something, in the form of energy. But work out how much of this energy there should be, and you come up with way too much. About 10^{120} times too much.

Together with theorists Thibaut Josset and Alejandro Perez at the University of Marseille in France, Sudarsky showed that energy creation through objective collapse might provide a closer fit. A big caveat is that the process would be compatible only with a slightly modified form of general relativity; accept that, and you’re in business. Or not quite. “Our rough calculations came surprisingly close,” says Sudarsky.

"But with the wrong sign." Their dark energy was pulling the universe together, not causing it to fly apart.

A big detail, you might say. But the work deliberately ignored the collapse effects of myriad energetic particles whizzing about at near light speed in the early universe, as theories of relativistic objective collapse simply aren't refined enough yet. Take those into account, says Sudarsky, and "things could come out all right". In a more speculative paper, he and Okon also claim that objective collapse can explain why the universe started in a state of exceptionally low disorder, or entropy, that has been increasing ever since. This continuous entropy increase matters to us – it is intimately connected to what we perceive as the one-way flow of time.

Bassi, who works independently on objective collapse models, thinks these ideas are among the best out there. "There is much more work to be done, to check whether the proposed resolution really works," he says. "But the starting point is encouraging."

The test of any good theory is, of course, experiment. The reason we believe standard quantum theory is its ability to explain, at least mathematically, experiments showing quantum objects behaving like waves in one situation and particles in another. These effects have now been observed with objects far larger than single particles – the record, set in 2013 at the University of Vienna in Austria, involves complex molecules some 20 million times the mass of the electron.

If Sudarsky is right, there is a natural size limit, after which objects begin to collapse spontaneously, removing the wave-like behaviour. Common sense tells us this threshold must be far smaller than that of everyday observations. "It should occur much before I send a cat through the apparatus," says Sudarsky. More exact experiments should be able to test the predictions of various objective collapse models. Hendrik Ulbricht at the University of Southampton in the UK thinks such tests could be performed within a decade, by making silica beads as massive as 20 billion electrons pass through and interfere at slits made of laser light.

An alternative test is to look for the excess energy that objective collapse theories predict should arise from spontaneous wave function collapse. Though near infinitesimal here on Earth, this should still be present as an all-pervading background noise that would disrupt the most sensitive experiments, like static muddying an analogue radio broadcast. In 2016, a team in Italy, including Bassi, cooled a vibrating cantilever to within a whisker of absolute zero and found deviations in its regular to-ing and fro-ing only from the tiny remaining thermal energy, nothing more. That established an upper bound on objective collapse noise, ruling out one particular incarnation, but leaving most intact.

For Sudarsky, this newfound testability provides an impetus to make objective collapse theory even more persuasive. It's an uphill battle to win hearts and minds in the face of one of the most successful theories ever devised. But then, understanding why the simple act of looking appears to create the world around us would be a big prize. ▮

QUANTUM BAYESIANISM

Is there an even simpler answer to the quantum measurement problem – that the uncertainty about the state of reality before a measurement is all in the mind?

DAVID MERMIN thinks he has something sensible to say about interpreting quantum theory. An atomic physicist at Cornell University in Ithaca, New York, he has spent most of his half-century-long career rejecting philosophical musings about the nature of quantum theory. A few years back, he had an epiphany. We can solve our quantum conundrums, by abandoning the ingrained idea that we can achieve an objective view of reality. According to this provocative idea, the world is not uncertain – we are.

It is not Mermin's idea: in fact, he spent more than a decade arguing against it with its originators, Carlton Caves of the University of New Mexico in Albuquerque, Christopher Fuchs of the Perimeter Institute for Theoretical Physics in Waterloo, Canada, and Rüdiger Schack of Royal Holloway, University of London.

Known as quantum Bayesianism, its ideas stem from reassessing the meaning of the wave function probabilities that seemingly govern the quantum world. Conventionally, these are viewed as "frequentist" probabilities. In the same way that you might count up many instances of a coin falling heads or tails to conclude that the odds are 50/50, many measurements of a quantum system tell you the relative frequency of its multiple states cropping up.

Despite its limitations, not least when dealing with single, isolated events, frequentist probability is popular throughout science for the way it turns an observer into an entirely objective counting machine. But an alternative, older approach to probability was devised by English clergyman Thomas Bayes in the 18th century. This is the sort of probability that crops up in a statement such as "there's a 40 per cent chance of rain today". Its value is not objective or fixed, but a fluid assessment based on many changing factors, such as current air pressure and how similar weather systems developed in the past. Acquire a new piece of information – see a bank of threatening cloud when you open the curtains in the morning, for example – and you might well update your prognosis to a 90 or 100 per cent chance of rain. The actual likelihood of rain has not changed; but your state of knowledge about it has.

The central argument of quantum Bayesianism, or QBism, is that, by applying this more subjective type of probability to the quantum world, whole new vistas open up. Measure the spin of an invisible electron, say, and you acquire new knowledge, and update your assessment of the probabilities accordingly, from uncertain to certain. Nothing needs to have changed at the quantum level. Quantum states, wave functions and all the other probabilistic apparatus of quantum mechanics do not represent objective truths about stuff in the real world. Instead, they are subjective tools that we use to organise our uncertainty about a measurement before we perform it. In other words: quantum weirdness is all in the mind. "It really is that simple," says Mermin.

For Mermin, the beauty of the idea is that the paradoxes that plague quantum mechanics simply vanish. Measurements do not "cause" things to happen in the real world, whatever that is; they cause things to happen in our heads. Spooky action at a distance is an illusion too. The appearance of a spontaneous change is just the result of two parties independently performing measurements that update their state of knowledge.

As for that shifty split, the "classical" world is where acts of measurements are continuous, because we see things with our own eyes. The microscopic "quantum" world, meanwhile, is where we need an explicit act of measurement with an appropriate piece of equipment to gain information. To predict outcomes in this instance, we require a theory that can take account of all the things that might be going on when we are not looking. For a QBist, the quantum-classical boundary is the split between what is going on in the real world and your subjective experience of it.

Quantum theorist William Wootters of Williams College in Williamstown, Massachusetts, thinks this is the most exciting interpretation of quantum theory to have emerged in years, and points to historical precedents. "It addresses Schrödinger's concern that our own subjective experience has been explicitly excluded from physical science, and both requires and provides a place for the experiencing subject," he says.

For Schack the strongest sign that QBism is on the right track is a thought experiment called Wigner's friend. Imagine you are standing outside a closed room where a friend is about to open the box containing Schrödinger's cat. Your friend witnesses a clear outcome: the cat is either alive or dead. But you must assign a set of probabilities based on a superposition of all the possible states of the cat and the reports your friend might make of it. Who's right? Both, say QBists: there is no paradox if a measurement outcome is always personal to the person experiencing it.

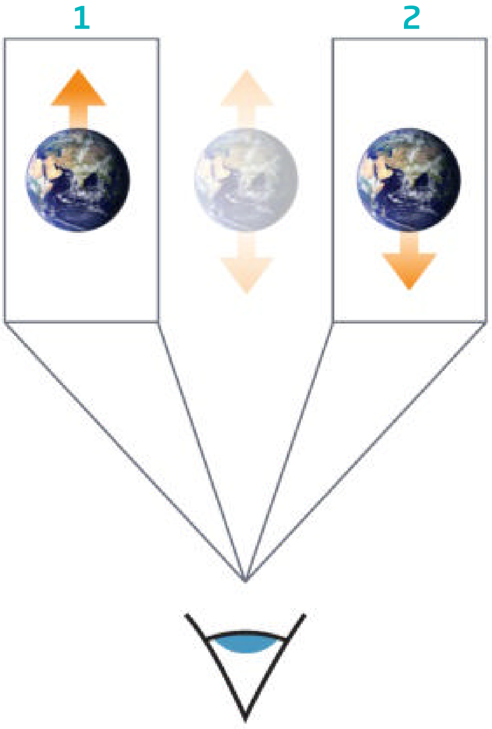
You might wonder whether all this matters, given that quantum theory does such a stupendous job of describing the world and supplying us with technological innovation. That is true up to a point, says Rovelli – but our lack of intuitive understanding hampers our search for some greater theory that can embrace all of physics from the smallest to the largest scales. "If we want to better understand the world, for instance, for quantum gravity or for cosmology, it does matter," he says.

Faced with the prospect of abandoning scientific objectivity, the temptation to shut up and calculate might be as strong as ever. But perhaps quantum Bayesianism provides a way to have our cake and eat it. Shifting quantum theory's weirdness into our own minds doesn't diminish our power to calculate with it – but might just make us shut up about how shocking it all is. ▮

UNCERTAIN UNCERTAINTY

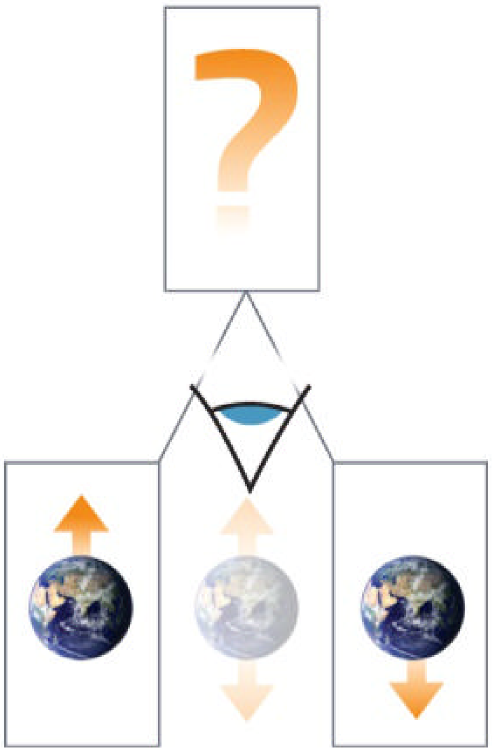
According to quantum Bayesianism, quantum fuzziness just reflects our lack of knowledge of the world

STANDARD QUANTUM PICTURE

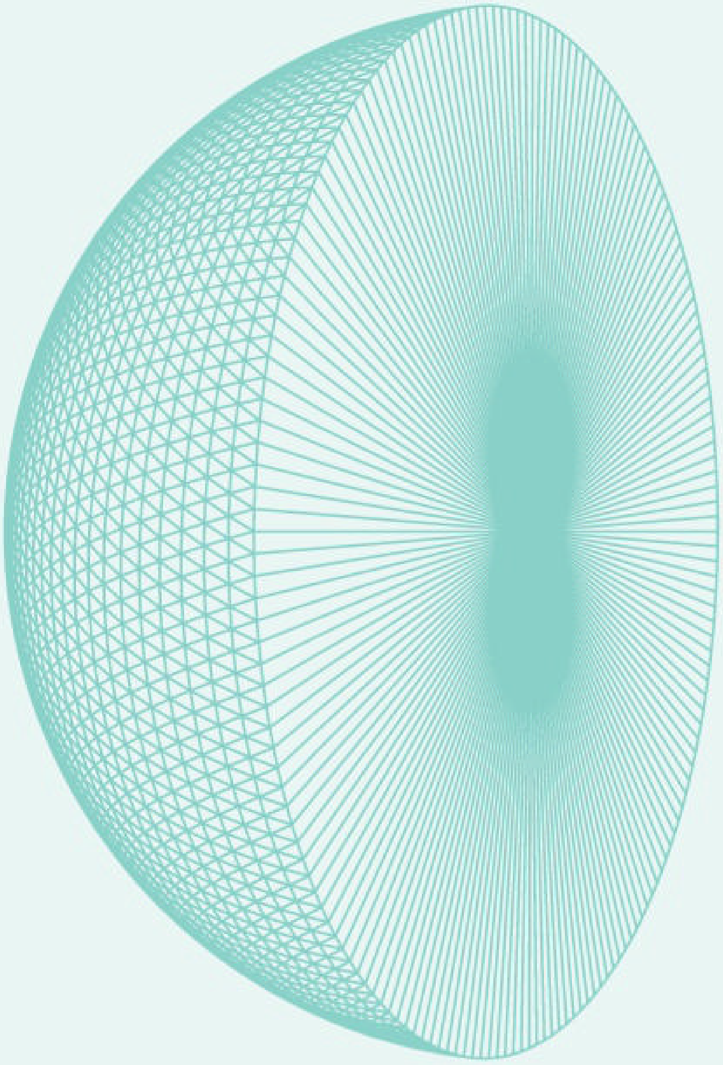


Objects in the quantum world exist in a fuzzy combination of states. The act of measuring forces them to adopt a specific state (1 or 2)

QUANTUM BAYESIANISM



The quantum states are all in our minds – they are just a fluid tool we use to understand our variable experiences of the world



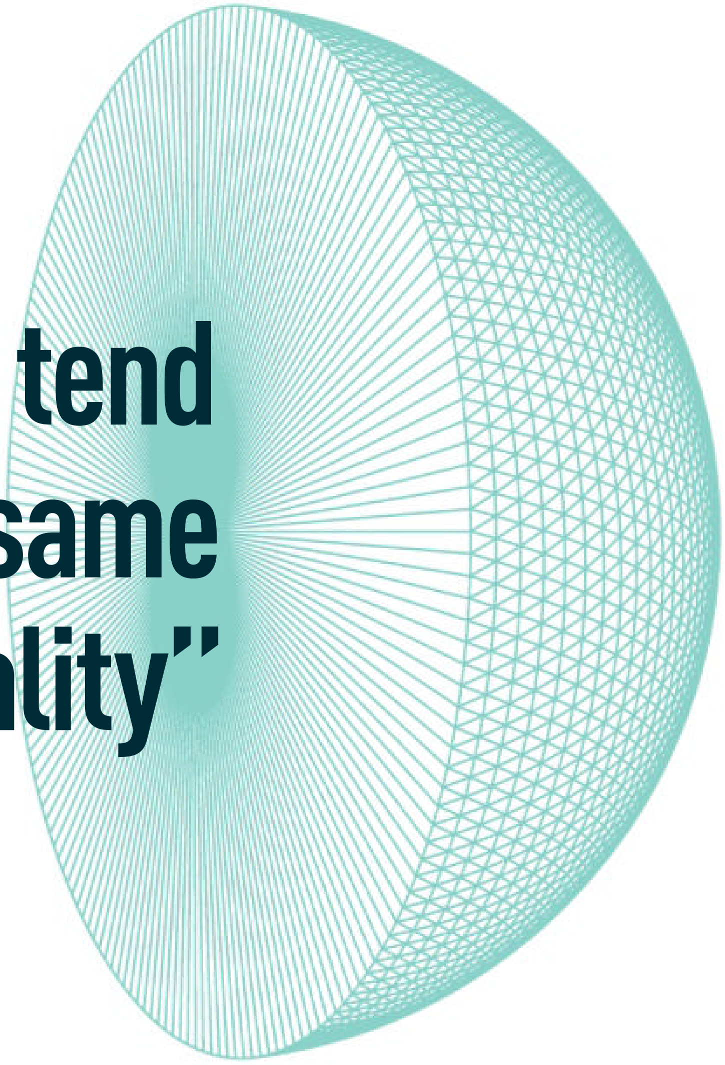
EMERGENT OBJECTIVE REALITY

Ideas about objective collapse or the simple non-existence of quantum fuzziness don't impress everyone. Could it be that our subjective experience has more to do with how reality is constructed than we give it credit for?

JOHN WHEELER at Princeton University once said that we live in a "participatory universe" – one that can't be meaningfully described without invoking our active involvement. It certainly does seem that wave function collapse from many possibilities to one observed reality hinges on some kind of intervention. "Nothing is more astonishing about quantum mechanics," Wheeler wrote, "than its allowing one to consider seriously… that the universe would be nothing without observership."

If you take quantum mechanics seriously, some element of observer-dependent subjectivity seems impossible to avoid. Enter Markus Müller, the self-described "madman" and a theorist at the University of Vienna. His answer is to represent each individual's experience at every instant as a string of bits of information – 1s and 0s, like binary computer code. Each observer's history then consists of a walk through the various possible bit strings, and the probability of going from one to the next would be random but conditional: it must take the history of experiences into account. The idea, says theorist Giulio Chiribella at the University of Hong Kong, "is to think of our experience as a movie made of many frames and to ask

“Different observers tend to converge on the same interpretation of reality”



the question, given the frames I have seen so far, what frame will I see next?”

You would think that such a picture could hardly be less likely to give rise to what we experience: a universe governed by laws and producing facts that are, as far as we can tell, the same for you as for me. But when Müller used the methods of algorithmic information theory to figure out what sequences of bit strings are likely, he found something remarkable.

As these random experiences stack up, the conditional probability of the next experience, as described by a string of bits, tends to be higher for simpler bit sequences than for complex ones. This makes it look as if there is a fairly simple algorithm generating the bit strings. So the observer deduces a simple “model” of reality, characterised by regular and comprehensible laws that smoothly connect one experience to the next.

This seems deeply odd: how can randomness give rise to this apparently law-bound behaviour? It’s a little like the way we understand a gas. Although in principle all possible configurations of its molecules are allowed, the probability distribution of particle speeds we see has a simple bell-shaped curve, and the particles are distributed in space with bland uniformity. Out of that come simple laws relating to things we can easily measure: pressure, temperature and volume. Those laws aren’t written into the gas particles themselves; they are an emergent property of the probabilities of different configurations.

“The remarkable thing is that a notion of an objective external world emerges automatically in the long run,” says Müller. What’s more, “different observers will tend to agree on properties of that external world”. That’s because according to algorithmic information theory, the probabilities of bit strings for different observers will tend to converge on the same distribution – so they will agree on what the “laws of the world” are. “Overall, the ‘movie’ is likely to be simple and different observers can generally agree on some aspects of the plot,” says Chiribella.

The surprises don’t stop there. This emergent reality should have just the qualities we see in quantum physics, where objects can show wave-like properties and behave in “non-local” ways, when a measurement on one particle can seem instantaneously to influence the state of another separated in space.

The upshot is that from the most minimal assumptions about the probabilities of what our personal experiences will contain, you can recover a world like the one we know. “The world could still look something like how we experience it, even though in truth it would be mind-bogglingly different,” says Müller. ▮

It is perhaps the most bizarre solution to the quantum measurement problem – but it has increasing numbers of adherents. Perhaps the answer lies not in wave functions collapsing, but worlds dividing – a concept with truly mind-blowing consequences for reality, but also for our sense of self.

THE MANY WORLDS INTERPRETATION

WHILE a graduate student at Princeton University, Hugh Everett III called the enforced separation of the quantum world from the everyday, classical one a "monstrosity", and decided to find out what happened if the wave function did not collapse. The mathematics he came up with showed that the universe would split every time a measurement is made – or in human terms, whenever we make a decision with multiple possible outcomes. That, in a nutshell, is the many-worlds interpretation.

In this interpretation, every decision you take in this world creates new universes: one for each and every choice you could possibly make. There's a boundless collection of parallel worlds, full of innumerable near-copies of you and everyone else.

The leading physicists of Everett's day, in particular Niels Bohr, one of the fathers of quantum mechanics, couldn't stomach it. They couldn't cope with the idea that every decision we make creates new universes, one for all possible outcomes. Everett had to publish a watered-down version of his idea. Thoroughly disgruntled, he left physics.

If Everett is correct – and many physicists now think he is – your actions shape the course not just of your life, but of the lives of your duplicates in other worlds.

"In the many-worlds interpretation, when you make a choice the other choices also happen," says David Deutsch, a quantum physicist at the University of Oxford. "If there is a small chance of an adverse consequence, say someone being killed, it seems on the face of it that we have to take into account the fact that in reality someone will be killed, if only in another universe."

Does this matter? Most of us try to live by a moral code because we believe the things we do affect other people, even ones we'll never meet. We worry about how our shopping habits affect workers in distant countries; about as-yet-unborn generations suffering for our carbon emissions. Deutsch points out that we readily accept that attempted murder has moral implications, albeit less serious than actual murder. So why shouldn't we afford some consideration to our other selves?

Max Tegmark, professor of physics at the Massachusetts Institute of Technology, understands the quandary. A leading advocate of the multiverse, he's thought long and hard about what it means to live in one. "I feel a strong kinship with parallel Maxes, even though I never get to meet them. They share my values, my feelings, my memories – they're closer to me ›

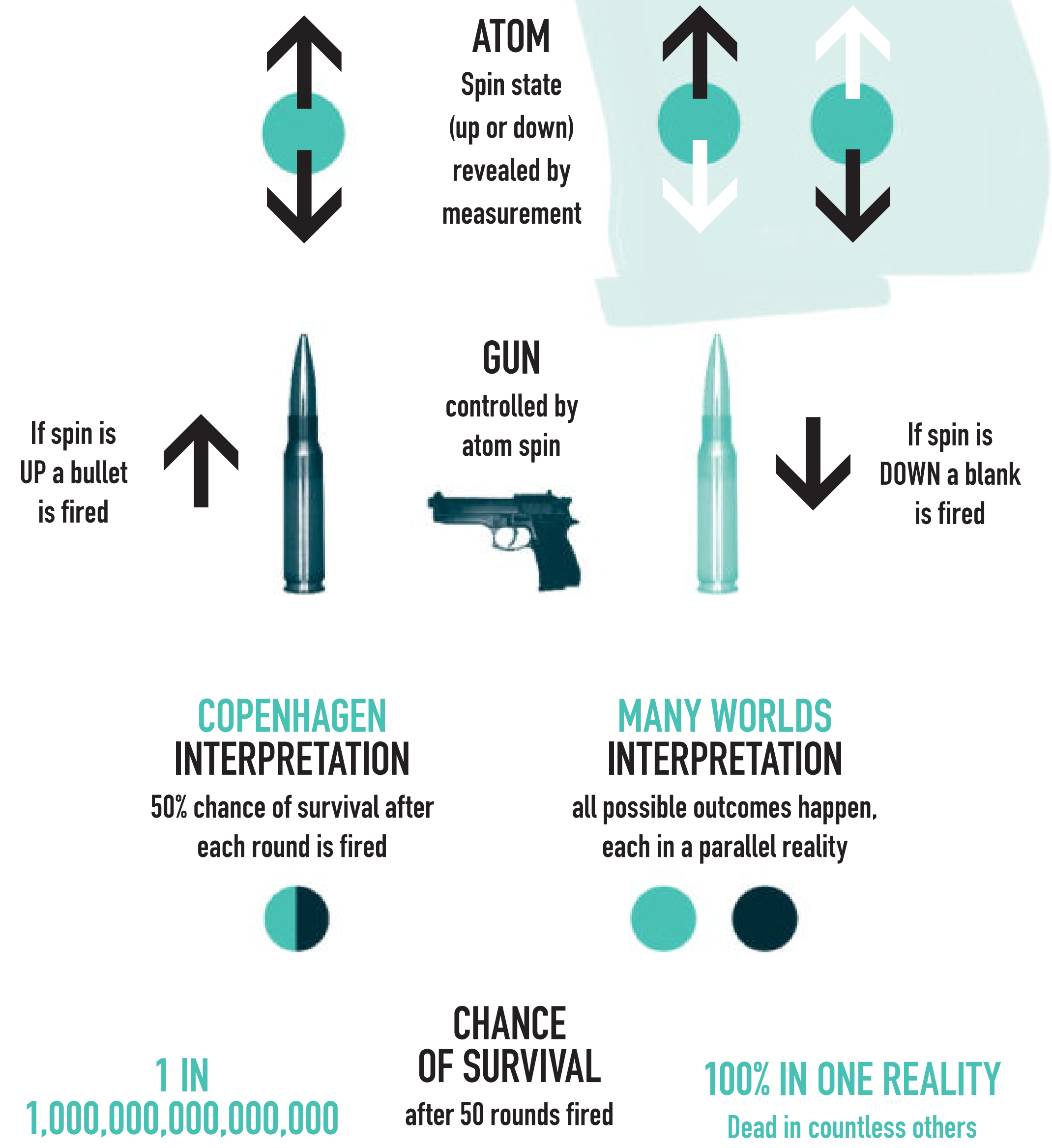
QUANTUM RUSSIAN ROULETTE

Ever fancied playing the role of Schrödinger's cat? You'll need a gun whose firing is controlled by a quantum property, such as an atom's spin, which has two possible states when measured.

If the Copenhagen interpretation is right, you have the familiar 50-50 odds of survival. The more times you "play", the less likely you are to survive.

If the multiverse is real, on the other hand, there always will be a universe in which "you" are alive, no matter how long you play. What's more, you might always end up in it, thanks to the exalted status of the "observer" in quantum mechanics. You would just hear a series of clicks as the gun failed to fire every time – and realise you're immortal. But be warned: even if you can get hold of a quantum gun, physicists have long argued about how this most decisive of experiments would actually work out.

GETTY IMAGES



ATOM
Spin state (up or down) revealed by measurement

GUN
controlled by atom spin

If spin is UP a bullet is fired

If spin is DOWN a blank is fired

COPENHAGEN INTERPRETATION
50% chance of survival after each round is fired

MANY WORLDS INTERPRETATION
all possible outcomes happen, each in a parallel reality

CHANCE OF SURVIVAL
after 50 rounds fired

1 IN 1,000,000,000,000,000

100% IN ONE REALITY
Dead in countless others

than brothers," he says.

Taking the cosmic perspective makes it difficult for Tegmark to feel sorry for himself: there's always another Max who has it worse than him. If he has a near-miss while driving, he says he takes the experience more seriously than he did before he knew about the multiverse. "The minimum tribute I can pay to that dead Max is to really think through what happened and learn some lessons."

Tegmark is obviously a multiverse believer. Once, he would have been an outsider. When Everett first proposed many-worlds it met with a scornful reception. Everett struggled to get it published, and eventually left academia in disgust. But its elegant explanations for some puzzling quantum phenomena have convinced more and more physicists over the past 50 years. "Multi-universe physics has the same kind of experimental basis as the theory that there were once dinosaurs," says Deutsch.

Nor can we avoid its consequences. Every time we make a decision that involves probability – such as whether to take an umbrella in case of rain – our decision causes the universe to branch, explains Andreas Albrecht at the University of California, Davis. In one universe, we take the umbrella and stay dry; in another, we don't, and we get wet. The fundamental variability of the universe forces such choices upon us. "There's no escaping them," says Albrecht.

That's a momentous realisation. We're living in a time akin to Copernicus realising that Earth wasn't at the centre of the universe, or when Darwin realised that humans were not created separately from the other animals. Both of those realisations reshaped our conception of our place in the universe, our philosophy and morality. The multiverse looks like the next great humbler of humanity.

It's tough even for physicists to get their heads around the implications of the multiverse. When Tegmark's wife was in labour with Philip, their eldest son, he found himself hoping that everything would go well. Then he admonished himself.

"It was going to go well, and it was going to end in tragedy, in different parallel universes. So what did it mean for me to hope that it was going to go well?" He couldn't even hope that the fraction of parallel universes where the birth went well was a large one, because that fraction could in principle be calculated. "So it doesn't make any sense to say 'I'm hoping something about this number'. It is what it is."

Tegmark says many worlds has made him think differently about life. He sometimes fears doing something because it feels too big a deal. But then he realises that in the grander context of the multiverse, it's not big at all – and he just does it. "The multiverse has definitely made me a happier person," he says. "It's given me courage to take chances to be bold in life."

Philosopher David Papineau of King's College London suggests the multiverse can certainly give you a broader perspective on life. "Say you put your money on a horse which you think is a very good bet," he says. "It turns out that it doesn't win, and you lose all your money. You think, 'I wish I hadn't done that.' But you brought benefits to your cousins in other universes where the horse won. You've just drawn the short straw in finding yourself in the universe where it lost. You didn't do anything wrong. There's no sense that the action you took earlier was a mistake."

According to Papineau, acting rationally is the key to thriving in the multiverse. With orthodox thinking, there are two ways of evaluating risky actions, he explains. First, did you make the choice that was most in line with the odds? If we needed money, and my stake had been proportionate, it might have been. Second, did it work out well? There are any number of reasons it might not – the horse might fall, or just defy the odds and trail in last.

It offends Papineau that these two ways of being "right" – choosing wisely and getting lucky – don't go hand-in-hand. "The idea that the right thing to do might turn out to have been the wrong thing seems to me to be a very ugly feature of orthodox thinking," he says. This doesn't arise in the many-worlds interpretation, where every choice is made and every outcome occurs. That leaves no place for hope or luck, but nor does it leave room for remorse. It's an elegant, if cold-blooded, way to look at things.

For Don Page, a theoretical physicist at the University of Alberta in Edmonton, Canada, this elegance goes far beyond human actions. Page is both a hard-core Everettian and a committed Christian. Like many modern physicists, he agrees with Everett's stance that collapsing the wave function is unnecessarily complicated. What's more, for Page it has a happy side effect: it explains why his God tolerates the existence of evil.

"God has values," he says. "He wants us to enjoy life, but he also wants to create an elegant universe." To God the importance of elegance comes before that of suffering, which, Page infers, is why bad things happen. "God won't collapse the wave function to cure people of cancer, or prevent earthquakes or whatever, because that would make the universe much more inelegant."

For Page, that is an intellectually satisfying solution to the problem of evil. And what's more, many worlds may even take care of free will. Page doesn't actually believe we have free will, because he feels we live in a reality in which God determines everything, so it is impossible for humans to act independently. But in the many-worlds interpretation every possible action is actually taken. "It doesn't mean that it's fixed that I do one particular course of action. In the multiverse, I'm doing all of them," says Page.

There are limits to Page's willingness to leave his fate to the multiverse, however. He was once offered $1 million to play quantum Russian roulette. This amounts to playing the role of Schrödinger's cat. You'll need a gun whose firing is controlled by a quantum property, such as an atom's spin, which has two possible states when measured. If the multiverse is real, there always will be a universe in which "you" are alive, no matter how long you play. What's more, you might always end up in it, thanks to the exalted status of the "observer" in quantum mechanics. You would just hear a series of clicks as the gun failed to fire every time – and realise you're immortal.

Page thought about it, then declined: he didn't like the thought of his wife's distress in the worlds where he died.

Nonetheless, Page also values the multiverse for the perspective it offers. "One of my teenage children wants to get a motorcycle, which my wife and I think is pretty dangerous," Page says. "But if I say: 'Okay, maybe most of the time you'd survive, but there's going to be some part of you, some branch, in which you get seriously maimed in a motorcycle accident'... Maybe I'll try it."

David Deutsch of the University of Oxford is probably the most hard-core of Everettians, and he has a surprising perspective on all this. "Decision theory in the multiverse tells us that we should value things that happen in more universes more, and things that happen in fewer universes less," he explains. "And it tells us that the amount by which we should value them more or less is, barring exotic circumstances, exactly such that we should behave as if we were valuing the risks according to probabilities in a classical universe." So the right thing to do remains the right thing to do.

If he's right, his conclusion only reinforces what his peers recommend: the best way to live in the multiverse is to think carefully about how you live your life in this one. ∎

NONE OF THE ABOVE?

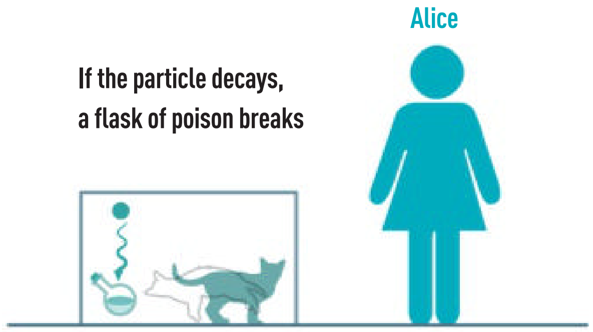
With no clear way of probing the various rival quantum interpretations by experiment, which one you choose to believe is a matter of just that – belief. Is there a better way?

HAVING KITTENS

Three generations of thought experiment have helped us explore what quantum theory says about the character of reality. The latest may create a paradox that can't be explained away

SCHRÖDINGER'S CAT

In Erwin Schrödinger's original thought experiment, a quantum particle's decay defines whether a cat lives or dies. Before Alice looks in the box, quantum theory appears to suggest the cat is both alive and dead



FOR theorist Renato Renner at the Swiss Federal Institute of Technology in Zurich, the deadlock between quantum interpretations wasn't acceptable. He set out to break it with a more sophisticated Schrödinger's cat-type thought experiment that he devised with his colleague Daniela Frauchiger, originally in 2016. It involves not one, but two "Wigner's friend" arrangements, in which someone is outside the lab observing whoever is observing the state of the cat.

↑
Turn back to page 39 for more on the basic Wigner's friend set-up

In the first, an experimentalist called Alice waits outside a lab in which her friend is doing a quantum experiment, a kind of coin flip carried out using quantum technology whose outcomes, for the purposes of later maths, are weighted 2/3 one way and 1/3 the other. In parallel, Bob has his eye on a second lab where his friend is making a Schrödinger's cat-type measurement (see diagram).

The essential twist is that Alice and Bob's friends' labs – and with them Alice and Bob's friends themselves – are in a kind of quantum superposition in which Bob's friend's measurement probabilities are determined by which way Alice's friend's biased coin flips. This means that when Alice and Bob perform a particular measurement on their respective friend's lab, they can know for definite what happened with their friend's experiment, but also have a clue as to what must have happened with the other friend's experiment. "It's a mixture between not completely opening the boxes but still comparing what's inside," says Renner.

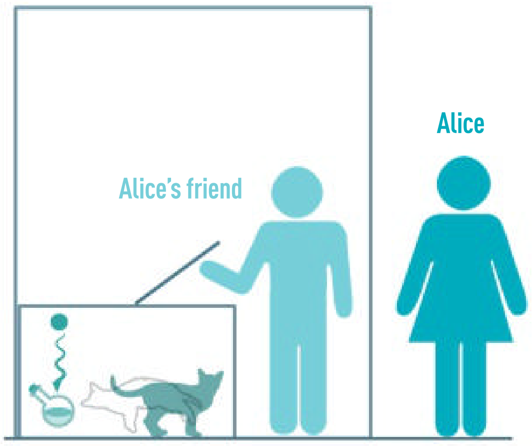
One after the other, the four agents perform their measurements. In analysing what happens, the thought experiment makes three basic assumptions about knowledge. First, the same theory of knowledge, in this case quantum theory, applies everywhere at all times. Second, measurements always have consistent outcomes everyone can agree on. Third, alternative facts aren't allowed: if someone measures something, you can't swear blind the opposite has happened.

Such assumptions serve us well in similar problems of hidden information in the classical world. But it turns out that in the quantum world they create a no go. Working through the mathematics shows that while on most occasions all observers end up in a consistent knowledge state, on average one time in 12 Alice and Bob see different realities when they open the lab doors.

The Frauchiger-Renner paradox hits a level of weirdness that exceeds the previous feline thought

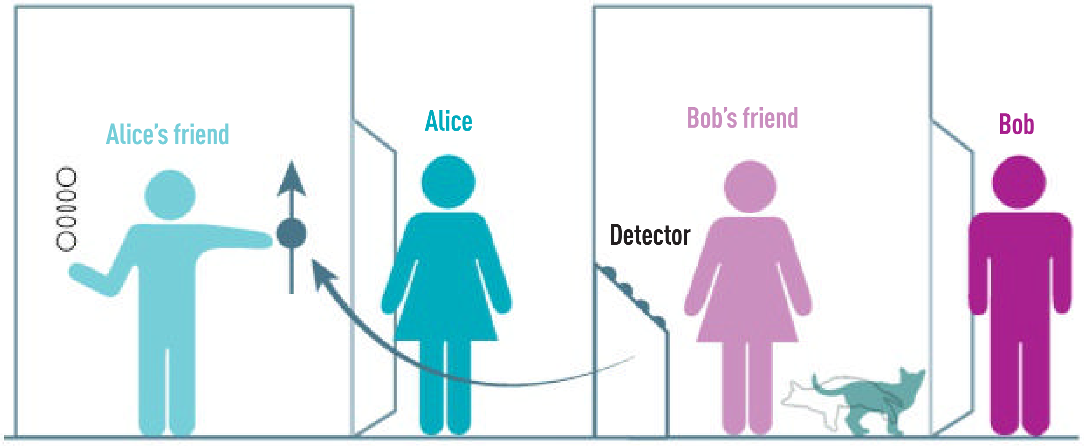
WIGNER'S FRIEND

A later version painted in an extra observer. To Alice outside the lab, the cat's state remains undefined even when Alice's friend inside knows it for definite. Any interpretation of quantum theory must then also explain how observers can infer contradictory realities



THE FRAUCHIGER-RENNER PARADOX

In this more complex set-up, Alice and Bob sometimes observe different outcomes with their own eyes. Since no previous interpretation of quantum theory easily allows for multiple, really existing truths in the same universe, it suggests they are all lacking something



Alice's friend flips a coin and uses the result to set a property of a quantum particle

Bob's friend measures that property, with the result linked to the cat's survival

When Alice and Bob open their doors, they sometimes see conflicting results

experiments. Previously, there was a dead-and-alive cat that you never got to see, leaving room for doubt that it ever existed. In this experiment, all the measurements have been made and it is as if the dead-and-alive cat is right there in front of you. There is no single truth everyone involved in the measurements can agree on. "The resolutions of the old paradoxes of Schrödinger's cat and Wigner's friend don't apply to this one," says Renner. That disturbing conclusion is writ large in the title of the paper that, after many refinements, Frauchiger and Renner finally published in 2018: "Quantum mechanics cannot consistently describe the use of itself".

It isn't yet possible to act out the thought experiment. We are a long way from having the technical know-how to connect quantum experiments in the way it requires. But it isn't pie in the sky either. A related, if not as certainly damning, thought experiment has been carried out for real and the predictions of alternative facts stood up. Renner thinks that when quantum computers properly come to fruition, you might use them as the observers and so see how his scheme plays out for real.

In the meantime, the claim that quantum theory can't say which side of reality such an experiment will come down on is a weighty accusation. If the theory is the right way to explain reality's basic workings, it must have universal validity. So it should be able to describe a complex system involving people who are themselves using quantum theory, in much the same way as classical physics can be used to describe people performing a classical measurement with tape measure and stopwatch, say. But it can't. Apparently.

Since the paradox was first circulated, there has been lively discussion of its significance. Some think the result plain wrong, and that there is a faulty or hidden assumption that renders the thought experiment invalid. Of those who agree the paradox represents a new challenge, many think the resolution lies in loosening one of the three assumptions about the nature of knowledge that it relies on. At this price, one or other of the existing interpretations of quantum theory might provide a way out.

Take Renner's favoured many-worlds interpretation, which forgoes the part about alternative facts not being allowed – they are allowed, just in another universe. Renner initially thought this might work. But further investigation showed that there is no branch of the universe after the measurement where the answers of all four observers are consistent. "Before this thought experiment, I was relatively convinced that certain interpretations make sense," says Renner. "Now I think none of them can."

The reading of Nicolas Gisin at the University of Geneva in Switzerland, meanwhile, is that the first assumption about one consistent theory of ›

> “Quantum theory seems to make different statements for different observers”

knowledge is at fault, and that this favours his preferred interpretation, in which wave-function collapse is an objective feature of the universe. After a collapse, the rules of quantum theory cease to apply and the contradiction dissolves.

Others make similar claims for their favoured approaches. Loosen assumption two, for example, and you might allow a quantum Bayesianism approach, where all the uncertainty is in the eyes of the beholder. “Maybe what proves it really is something that has no clear solution is that people are not agreeing on what the solution might be,” says Renner.

But this may just be opening the stable door after the horse has crashed out through the side wall. We already knew that quantum theory is starkly incompatible with general relativity, Einstein’s theory of gravity, which kicks in on very large scales. In most situations, the two theories don’t meet, but at the points where they do – at the event horizon of a black hole, for example, or the first instant of the big bang – unresolvable paradoxes crop up.

Hypotheses that attempt to bridge the divide tend to work on the assumption that general relativity is wrong, because quantum theory can explain all the other fundamental forces of nature. Now we might have a different perspective. “This experiment suggests that quantum mechanics itself runs into problems when we go to large systems, without even talking about relativity,” says Renner.

Hardy agrees that further enlightenment lies in the search for ways to unite quantum theory and relativity – and that the discovery that quantum theory makes incontrovertibly contradictory statements for different observers under certain circumstances provides a valuable starting point.

He sees the situation as analogous to when general relativity replaced Newton’s earlier theory of gravity. Like quantum theory, Newtonian gravity was a good operational framework – you plugged in the numbers and it gave the right answers. But it didn’t give any physical picture of how gravity actually worked. It was only following up on the tiny instances where Newton’s theory got it wrong that led Einstein to his richer, physical picture of how the warping of space-time creates gravity. “The resolution of the problem didn’t come from any existing way of thinking, but from something entirely different,” says Hardy.

Hardy’s suggestion of where to look for a more powerful theory lies in borrowing ideas from relativity: ideas about different frames of reference and how they interrelate. “It seems like that might be the right mathematical framework to describe how to go between these different classical worlds,” he says. But what such a theory looks like is a huge work in progress. If it requires new physics, it might end up looking like an objective collapse model of the sort Gisin favours, Hardy speculates, with gravity having some part in the collapse mechanism. “But, of course, I don’t know.”

Renner and his colleagues are busy working to convince the doubters by programming a classical computer to simulate quantum computers acting as the observers, to at least prove that the reasoning of the thought experiment is sound. “I don’t expect any surprise,” he says. “The simulator will just show that there is a contradiction.” If so, the quantum cat really is among the pigeons. ▮

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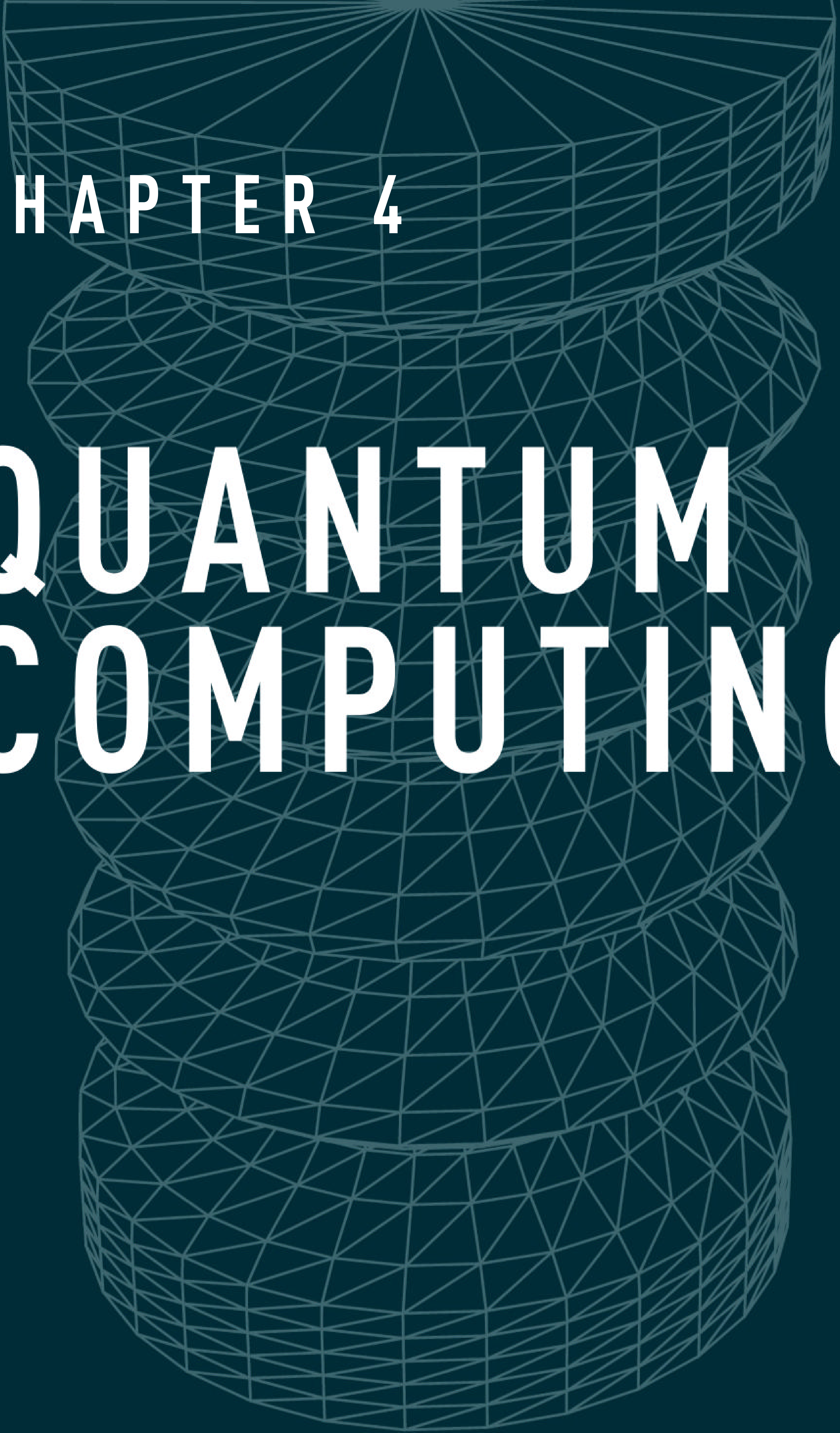


CHAPTER 4

QUANTUM COMPUTING

Up till now our discussions of quantum theory may have seemed rather abstract, and far removed from our everyday world. But quantum theory's practical applications have the potential to revolutionise our lives.

In some sense, they already have – the transistor, the laser and many other technologies already exploit basic quantum principles. But a new wave of quantum computing kit could exploit quantum weirdness to the full to give us technological superpowers. Vlatko Vedral starts with the basics.

WHAT QUANTUM COMPUTERS ARE MADE OF

PROFILE
VLATKO VEDRAL

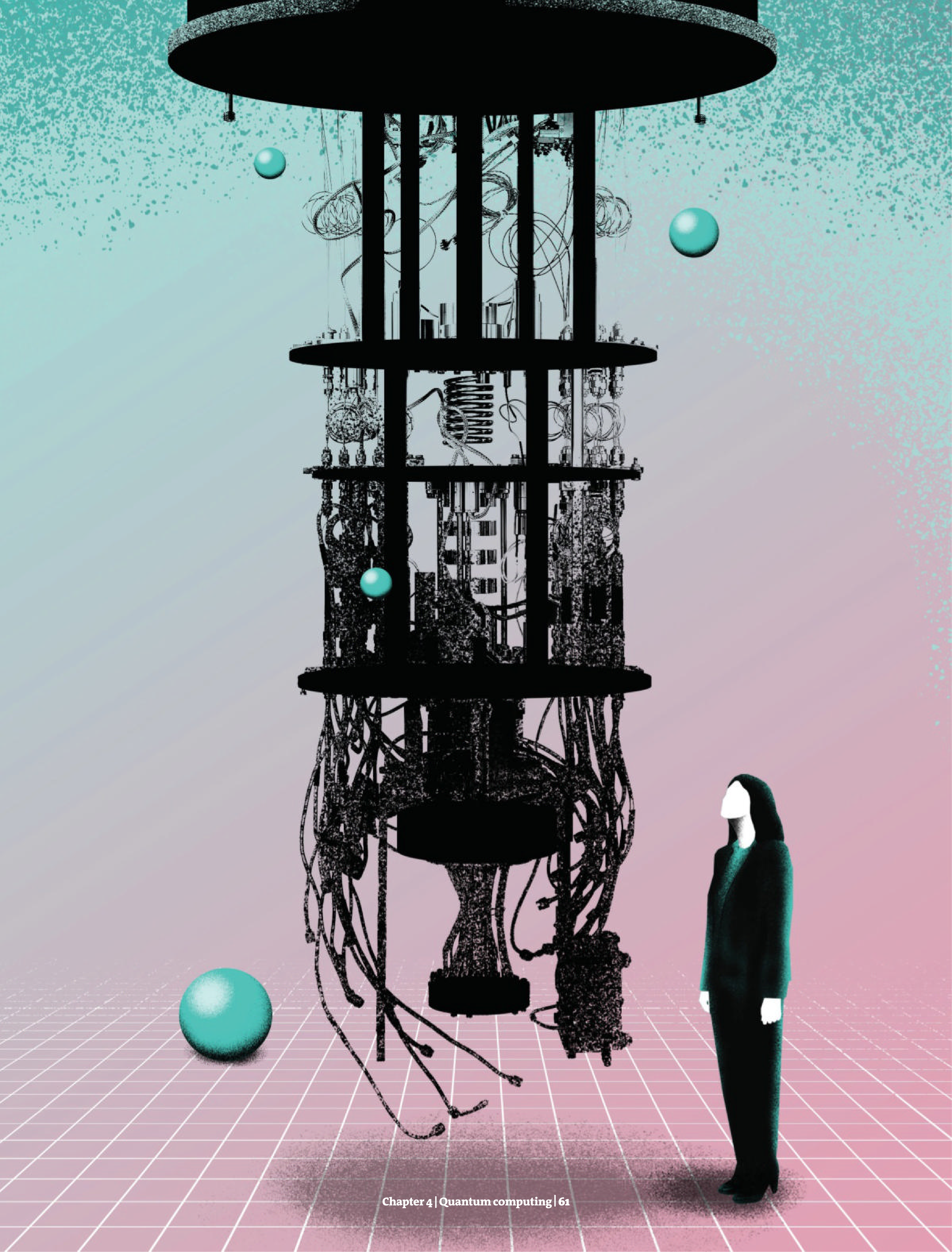
Vlatko Vedral is a physicist at the University of Oxford, where he researches quantum information and other ways of applying quantum physics beyond the microscopic domain

MARIO WAGNER

WHAT makes quantum computers so different? Conventional, classical computers process information using the presence or absence of electrical charge or current. These classical bits have two positions, on (1) and off (0). Semiconductor switches – transistors – flip these bits, making logic gates such as AND, OR and NOT. Combining these gates, we can compute anything that is in principle computable.

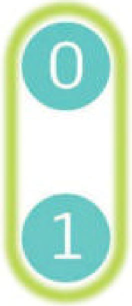
In quantum computation, the switching is between quantum states. Quantum objects can generally be in many states at once: an atom may simultaneously be in different locations or energy states, a photon in more than one state of polarisation, and so on. In general, quantum theory allows us to distinguish two of these states at any one time. In essence, a quantum bit, or qubit, is in a "superposition" that stores 0 and 1 at the same time.

That already suggests an enhanced computational capacity, but the real basis of a quantum computer's power is that the states of many qubits can be entangled with one another. This creates a superposition of all the possible combinations of the single-qubit states. Different operations performed on different parts of the superposition at the same ›



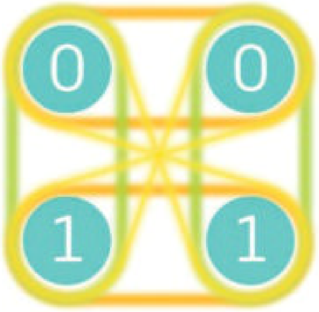
SUPERPOSITION

Quantum superposition and entanglement combine to allow information to be processed more efficiently and teleported over distances



One qubit encodes 0 and 1 simultaneously

ENTANGLEMENT



Two qubits store all four permutations simultaneously 00, 01, 10, 11

Similarly, three qubits store eight states, four qubits 16 states and so on – which gives an exponential increase in computing power

time effectively make a massively powerful parallel processor. The power increase is exponential: *n* qubits have the information processing capacity of 2^n classical bits (see diagram, above). A 400-qubit quantum computer would be like a classical computer with 10^{120} bits – far more than the number of particles estimated to exist in the universe.

In recent decades, we have done very well in cramming ever more transistors into classical computer chips. But the density of heat generated by constantly resetting these physical on-off switches now represents a fundamental barrier to further miniaturisation. Quantum computation can sidestep that barrier.

That's because by using the right manipulations you can flick between quantum states such as the polarisations of photons without expending any heat. This is no blank cheque for low-power computing, however. Reading and writing information to a quantum memory entails making measurements akin to flipping a classical switch, and will still generate some heat.

So what will it do? Computer scientists divide problems into "easy" problems, where the computational resources needed to find a solution scale as some power of the number of variables involved, and "hard" problems, where the resources needed increase in a much steeper exponential curve. Hard problems rapidly get beyond the reach of classical computers. The exponentially scaling power of a quantum computer could bring more firepower to bear, if not making the problems easy, then at least less hard.

A quantum speed-up is not a given, however: we first need a specific algorithm that tells us how to achieve it. For important, hard tasks such as factoring large numbers or searching a database, we already have recipes such as Shor's and Grover's algorithms (see "Quantum software", page 64). But for a mundane task such as listing all the entries in a database, the time or processing power required to solve the problem will always scale with the number of entries, and there will be no appreciable quantum speed-up.

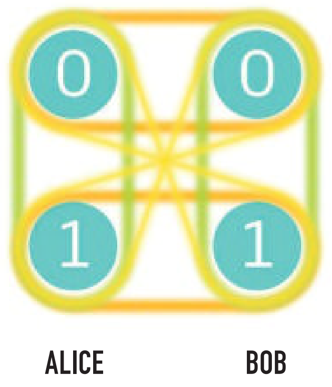
What might a quantum computer be good for? Physicist Richard Feynman's original motivation for thinking about quantum computers in 1981 was that they should be more effective than classical computers at simulating quantum systems – including themselves.

This sounds a little underwhelming, but many of science's thorniest practical problems, such as what makes superconductors superconduct or magnets magnetic, are difficult or impossible to solve with classical computers.

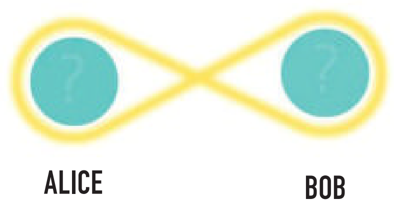
Quantum information theorists have already developed intricate algorithms for approximating complex, many-bodied quantum systems, anticipating the arrival of quantum computers powerful enough to deal with them.

The beauty is that such simulators would not be limited to existing physics: we could also use them to glean insights into phenomena not yet seen. Quantum simulations might tell us, say, where best to look in nature for Majorana particles, for example in complex many-bodied superconductor states. Since these particles, thought to be their own antiparticles, have properties that could make them ideally suited to

TELEPORTATION



Alice and Bob share a pair of entangled qubits



To transmit a 2-bit classical message (00, 01, 10 or 11), Alice measures her qubit, collapsing the superposition into one of its four possible states

Bob sees the consequence of the measurement in his own qubit, so knows which bits Alice had – without anything physical being transferred

making robust quantum memories, this raises the intriguing possibility of using quantum computers to suggest more powerful quantum computers.

All this presumes a quantum computer big enough to make a difference. However, making one is easier said than done. There are many ways of making the "qubits" for a quantum computer to crunch, from polarising light to cooling atoms to taming the collective motions of electrons. But any qubit must fulfil some stringent criteria, particularly in proving robust, or "coherent", in the face of buffeting from its surrounding classical environment. No single sort of qubit has yet ticked all the boxes, but we are making good progress. Let's discuss a few of the most promising ones.

Trapping ions is perhaps the most advanced method of making a quantum computer's qubits. Positively charged ions are caught in electromagnetic fields and cooled to a nanokelvin or so to reduce their vibrations and limit decoherence. Information is then encoded in the ions' energy levels and manipulated using laser light. That brings excellent initialisation success, accuracy and stable memory storage.

In 1995 David Wineland and his colleagues at the US National Institute of Standards and Technology in Boulder, Colorado, used trapped ions to create the first quantum logic gate – a controlled NOT (C-NOT) gate for disentangling entangled ions. In 2011, physicists from the University of Innsbruck, Austria, developed a 6-qubit trapped-ion computer that fulfilled the specifications for a universal quantum simulator that Richard Feynman had set out in 1981.

Decoherence and scalability remain interrelated problems, however. With a few entangled qubits the decoherence time is 1000 times the gate-switching time, but this rapidly reduces as qubits are added.

Then there are superconducting qubits. At temperatures of a few kelvin, electrons in some superconducting materials form entangled pairs, known as Cooper pairs, which flow without resistance and are peculiarly resilient against decoherence.

Superconducting quantum interference devices (SQUIDs) already exploit this effect to make incredibly sensitive measurements of electromagnetic fields. But electron movements and magnetic field states within a SQUID can also be manipulated using external fields to form the bits of a quantum logic device. SQUID qubits offer good initialisation and decoherence times, typically 10 or so times greater than the time taken to switch a gate.

The position, polarisation or just number of photons in a given space can also be used to encode a qubit. Though initialising their states is easy, photons are slippery: they are easily lost and do not interact very much with each other. That makes them good for communicating quantum information, but to store that information we need to imprint photon states on something longer-lived, such as an atomic energy state.

If we can nail that, quantum computing with photons is a promising concept, not least because the processing can be done at room temperature. In 2012, a team at the University of Vienna, Austria, used four entangled photons to perform the first blind quantum computation. Here a user sends quantum-encoded information to a remote computer that does not itself "see" what it is crunching. This may be a future › paradigm – totally secure quantum cloud computing.

Another possibility is that collections of many hundreds of atoms might make for good qubits when trapped, cooled and arranged using lasers in a two-dimensional array known as an optical lattice. The energy states of these atoms can encode information that can be manipulated using further lasers, as with trapped ions. We've mastered the basic techniques, but making a true quantum computer from cold atoms awaits establishing reliable entanglement among these aloof bodies.

Further off, but still promising is "topological" quantum computing. This depends on the existence of particles confined to two dimensions called anyons. These "topological" particles are peculiarly impervious to environmental noise, in principle making them excellent qubits. Particles such as Majorana fermions that fulfil some of the requirements of anyons have been fabricated in certain solids, but whether they are useful for practical quantum computing is still not resolved.

No overview of quantum computing would be complete without an attempt to answer the $64,000 (or possibly much more) question: are we likely to see working quantum computers in our homes, offices and hands any time soon?

Getting up to the several hundred qubits needed to fully and reliably outperform classical computers is largely a technological issue. Within a couple of decades, given improvements in cooling and trapping, as well as coupling with light, existing technologies of trapped ions and cold atoms may well be made stable enough in large enough quantities to achieve meaningful quantum computation.

The first large-scale quantum computers are likely to be just that: large-scale. They will probably require lasers for qubit manipulation and need supercooling, so are unlikely to appear in our homes. But if the future of much computing is in centralised clouds, perhaps this need not be a problem. ▮

QUANTUM SOFTWARE

The promise of quantum computers rests largely on two algorithms. One, developed in 1994 by Peter Shor, then of Bell Laboratories, provides a way for a quantum computer to speedily find the prime factors of large numbers. Classical computers effectively have to try to divide the given number by all possible prime factors (2, 3, 5, 7, 11 and so on) in turn, whereas quantum computers can do these divisions simultaneously.

Conventional encryption methods rely on the fact that classical computers cannot factorise efficiently. If Shor's algorithm were ever implemented on a large scale, encrypted information such as the PIN for your bank card would be vulnerable to hacking – and quantum cryptography would be the only viable defence. There is no need to worry just yet: demonstrations so far, for example using a 7-qubit nuclear-spin quantum computer, have been limited to demonstrating that the prime factors of 15 are 5 and 3.

In the longer term, an algorithm devised by physicist Lov Grover in 1996, also at Bell Labs, may become a quantum computer's greatest selling point. This provides a recipe by which a quantum computer can radically speed up how we access and search large bodies of data. Take the example of a database listing the contents of a library. Searching this database for a particular book with a classical computer takes a time that scales with the number of books, n; Grover's algorithm shows that for a quantum computer it scales with $\sqrt{n}$. For a library of a million books, this amounts to 1000 times faster.

Implementing such an algorithm has ubiquitous appeal: almost all computationally hard problems – for instance that of the travelling salesman who has to find the shortest route between a number of different cities – ultimately reduce to a search for the optimal solution.

A TIMELINE OF QUANTUM COMPUTING

1980

PAUL BENIOFF DESCRIBES THE FIRST QUANTUM MECHANICAL MODEL OF A COMPUTER, SHOWING THAT QUANTUM COMPUTERS ARE THEORETICALLY POSSIBLE.

1985

DAVID DEUTSCH DEVELOPS THE IDEA OF A UNIVERSAL QUANTUM COMPUTER: A WAY TO MATHEMATICALLY UNDERSTAND WHAT IS POSSIBLE ON A QUANTUM COMPUTER.

1994

PETER SHOR DEVELOPS "SHOR'S ALGORITHM", WHICH WOULD ALLOW A QUANTUM COMPUTER TO FACTOR LARGE NUMBERS MUCH FASTER THAN THE BEST CLASSICAL ALGORITHM.

1995

SEVERAL RESEARCHERS INDEPENDENTLY PROPOSE THE FIRST QUANTUM ERROR-CORRECTION METHODS TO AUTOMATICALLY FIX ERRORS THAT CAN EASILY ARISE IN A QUANTUM COMPUTER.

1997

QUANTUM TELEPORTATION, THE TRANSMISSION OF QUANTUM INFORMATION FROM ONE PLACE TO ANOTHER, IS FIRST DEMONSTRATED FOR SINGLE PHOTONS.

1998

RESEARCHERS AT THE UNIVERSITY OF OXFORD RUN A QUANTUM ALGORITHM FOR THE FIRST TIME, ON A 2-QUBIT QUANTUM COMPUTER.

2001

A TEAM AT IBM AND STANFORD UNIVERSITY USE SHOR'S ALGORITHM ON A 7-QUBIT QUANTUM COMPUTER, MADE FROM BILLIONS OF MOLECULES IN A TEST TUBE, TO FIND THE FACTORS OF 15.

2009

THE FIRST ELECTRONIC QUANTUM PROCESSOR IS BUILT. THE 2-QUBIT SUPERCONDUCTING CHIP IS MADE FROM MORE THAN A BILLION ALUMINIUM ATOMS IN A SUPERCONDUCTING ELECTRONIC CIRCUIT.

2012

JOHN PRESKILL COINS THE TERM "QUANTUM SUPREMACY" TO DESCRIBE THE POTENTIAL ABILITY OF QUANTUM COMPUTERS TO SOLVE PROBLEMS THAT CLASSICAL COMPUTERS CAN'T.

2013

GOOGLE, NASA AND THE US UNIVERSITIES SPACE RESEARCH ASSOCIATION ANNOUNCE THE LAUNCH OF A QUANTUM ARTIFICIAL INTELLIGENCE LAB.

2019

JANUARY

IBM UNVEILS ITS FIRST COMMERCIAL QUANTUM COMPUTER, THE 20-QUBIT Q SYSTEM ONE.

2019

OCTOBER

GOOGLE SAYS ITS QUANTUM COMPUTER TOOK 200 SECONDS TO COMPLETE A TASK THAT WOULD TAKE OUR MOST POWERFUL COMPUTER 10,000 YEARS, ACHIEVING QUANTUM SUPREMACY.

QUANTUM SUPREMACY

In October 2019, a new era of computing arrived when researchers at Google claimed their quantum computer had solved a problem that would take even the very best conventional machine thousands of years to crack.

REACHING “quantum supremacy” represented a long-sought stride towards realising the immense promise of quantum computers. It involved demonstrating that a quantum processor consisting of 54 superconducting quantum bits, or qubits, was able to perform a random sampling calculation – essentially verifying that a set of numbers is randomly distributed – exponentially faster than any standard computer.

Google’s Sycamore device did it in just 3 minutes and 20 seconds, although one of the qubits had to be turned off as it wasn’t working properly. According to Google, the calculation would have taken IBM’s Summit, the world’s most powerful supercomputer, some 10,000 years.

IBM immediately pushed back on that claim, insisting that with some clever classical programming, its machine can solve the problem in 2.5 days. IBM, which has its own 53-qubit quantum computer, prefers a higher threshold for quantum supremacy.

But even if you accept IBM’s claims at face value, Google’s quantum computer was still a big step forward. In August 2020 came another. Google researchers used a quantum computer to simulate a chemical reaction for the first time. The reaction was a simple one, but this marked a step towards finding a practical use for quantum computers.

Because atoms and molecules are systems governed by quantum mechanics, quantum computers are expected to be the best way to precisely simulate them. The team at Google used the company’s Sycamore device to simulate a diazene molecule, which consists of two nitrogen atoms and two hydrogen atoms, undergoing a reaction in which the hydrogen atoms move into different configurations around the nitrogens. The quantum simulation agreed with simulations the researchers performed on classical computers to check their work.

While this reaction may be relatively basic, and it isn’t necessary to have a quantum computer to simulate it, this work is still a big step forward for quantum computing. Scaling this algorithm up to simulate more complex reactions should be fairly easy: simulating reactions in bigger molecules will simply require more qubits and small tweaks to the calculation. Someday, we may even be able to develop new chemicals using quantum simulations. ■

THE POWER OF QUANTUM CRYPTOGRAPHY

There's one great fear about quantum computers – their superpowers could break the cryptography essential to secure much of modern online communication and commerce. The answer? Make the codes quantum too.

PRESENT-DAY cryptographic systems are in a precarious state. The security of all of our online purchases, bank transactions and personas rely on a single shaky assumption: that certain mathematical operations are hard to do. The best known of our modern encryption systems is called RSA. To encode data, it builds a key from two very large prime numbers. These are kept secret, but their product – a number thousands of binary digits long – is public knowledge. Data can be encoded using this public key, but only those with knowledge of the original numbers can decrypt it. RSA's security relies on the fact that there is no known shortcut to find the two starting numbers. The only ways to do it are almost interminable processes, such as trying all the possibilities one by one.

Or so we hope. "We cannot prove that these problems are inherently difficult," says Artur Ekert, a mathematician at Oxford University. It's not impossible that someone will discover a procedure allowing a conventional computer to quickly factorise the product of two huge primes. Maybe they already have and they're cleverly keeping it secret. If such an algorithm ever came to light, internet transactions would collapse, and financial deals and top secret government communications would be exposed. "It would truly be a catastrophe," says Michele Mosca of the Institute for Quantum Computing in Waterloo, Canada. "It's like a Y2K problem, except we don't know precisely when it might happen."

Even if we could prove that the factorisation problem is beyond the abilities of traditional computers, there are still quantum computers to consider. Because they compute using quantum phenomena they could consider all the possible primes at once. In 1994 the algorithm devised by mathematician Peter Shor, now at the Massachusetts Institute of Technology, showed this would be a speedy process. Simple quantum computers already exist and advanced machines able to realise Shor's idea can't be far off.

One way to reinvigorate our privacy is to fight fire with fire and employ quantum cryptography. This promises the ability to create keys that are entirely random, entirely unpredictable and totally inaccessible to spies.

Quantum cryptography hinges on the rules that govern particles like photons or electrons. Their properties, including polarisation for instance, take

›

multiple values at once, only snapping into sharp definition when measured. Use these properties as a basis for encryption and you preclude any attempt to peek at your key: that would change the result of the measurement, in effect destroying the key's tamper-proof seal. The technique has already been used to protect hospital data, financial transactions and voting in the Swiss general elections.

Current systems use a protocol where the person transmitting the key, usually referred to as Alice, releases a polarised photon and makes a measurement on it before sending it. Her listening partner, usually referred to as Bob, chooses a particular way to make a measurement of that polarisation, and then he and Alice use an unencrypted channel to compare the sort of measurements they did. This allows them to create one digit of a private key for use in encrypting messages. To build the entire key, Alice and Bob simply repeat the process.

You might think that's good enough, yet this type of quantum cryptography has weaknesses. "You always have to make some assumptions about certain pieces of equipment," says Vadim Makarov, one of Mosca's colleagues in Waterloo. Makarov is an expert at showing that those assumptions matter, having broken into many "secure" systems around the world. He is the first to admit that you have to go to fantastic lengths to exploit these weaknesses, but when it comes to state secrets, say, or large bank transactions, who's to say nobody would?

One example of such a vulnerability is known as the detection loophole. It arises because the efficiency of photon detectors is never perfect, making practical quantum cryptography a bit like sending multiple copies of your key via an army of couriers to an office that occasionally shuts for lunch. Alice has to send far more photons than would otherwise be necessary, because Bob can't detect them all. This intermittent detection means Alice and Bob can't be certain that their apparatus is working securely.

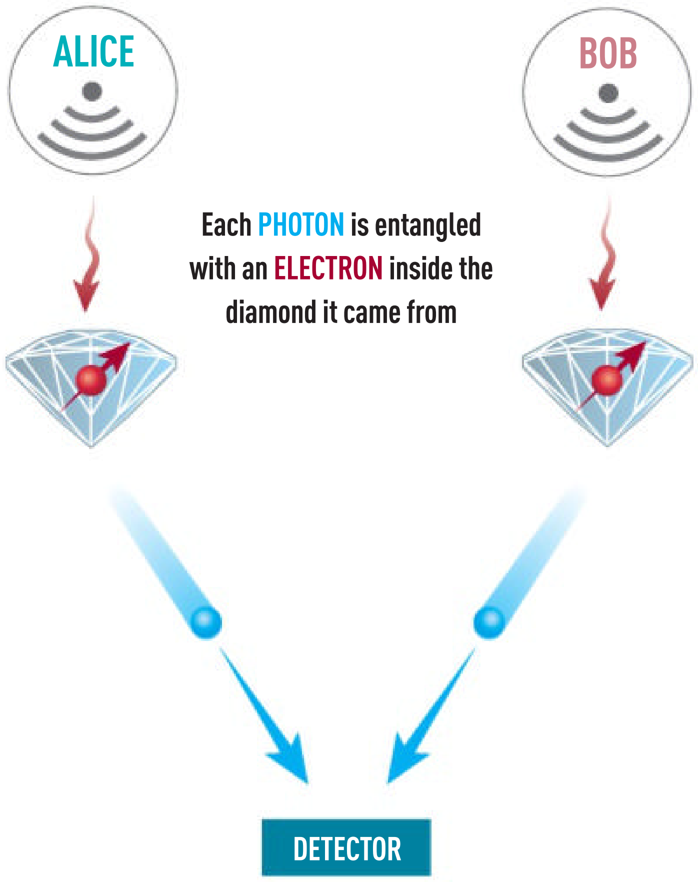
It's not impossible to dream up ways of solving these technical hitches, but there's another more subtle problem that comes as an unavoidable side dish and which takes us to the heart of the problem with trust.

Imagine you have bought a state-of-the-art quantum cryptography system. It might well come complete with a shiny certificate guaranteeing its security, but how do you know the manufacturer hasn't built in a covert back door that allows them to read and sell your secrets?

PRIVACY GUARANTEED

An experiment in 2015 beat the loopholes that compromise the security of existing quantum cryptography

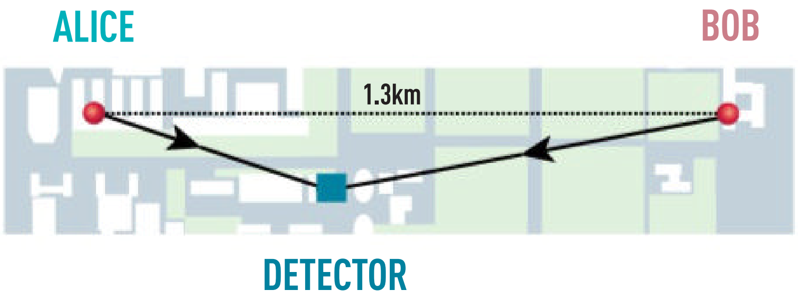
Alice and Bob each have a diamond and they fire a microwave pulse at it, causing the diamonds to emit a photon



Each PHOTON is entangled with an ELECTRON inside the diamond it came from

If the two photons arrive at the DETECTOR simultaneously, the entanglement gets transferred: now the electron in Alice's diamond is entangled with the electron inside Bob's diamond.

This allows Alice and Bob to have entangled particles without needing to exchange them – and that closes the loopholes



Aerial view of experiment at Delft University of Technology, the Netherlands

It’s hardly unthinkable. As soon as a new encryption technology is available, governments, corporations and intelligence agencies look for – or even demand – a hidden flaw that they can exploit. Maybe your machine is programmed to spit out a key matching what someone somewhere has on file. Or perhaps a side-channel logs a copy of any key you generate.

Here’s where device-independent cryptography comes in. It started when Ekert came up with a smart new form of quantum cryptography in 1991.

This protocol also uses a stream of photons and, just as before, Alice creates a string of random numbers by measuring a property of each. The twist is that this time Bob has a separate stream of photons from the same source, and his photons are “entangled” with Alice’s. Entangled photons are generated in pairs, and their properties are subtly connected. If Alice has one of a pair, and Bob has the other, they can perform measurements on their respective photons that will help them create each digit of a shared key.

Until 2004, Ekert’s idea was just another way of doing quantum cryptography, subject to the same loopholes. But that changed when Antonio Acín of the Institute of Photonic Sciences in Barcelona, Spain, and colleagues realised that this version of cryptography contained a way to check the trustworthiness of the manufacturer. The implications are profound: with this protocol, you could buy the machine from your worst enemy and still be certain that it couldn’t leak your secrets. “It came as a surprise to me,” Ekert says. “Sometimes your inventions can be cleverer than you are.”

The rules of quantum theory say that the link between two entangled particles is “monogamous”: there is no correlation with anything else and so no information can escape to an eavesdropper. Acín’s neat insight was that you can prove whether this is the case using something known as a Bell test.

First set out by physicist John Bell in 1964, the test aims to determine whether two sets of numbers are more highly correlated than can be achieved by chance. “The more they are correlated together, the less they can be correlated with anything outside,” Ekert says. If your system passes the Bell test, you have a cast-iron guarantee of three things. First, that your key is generated on the fly and thus not predictable. Second, that its digits have an inherent randomness, and thus can’t be guessed. Third, perhaps most importantly, no one is tapping into your key transmission using a back door. If they were, the correlations would be tainted.

There was just one problem with the scheme: no one had built a fully watertight experimental set up to conduct the Bell test. It comes down to the same problems that plague today’s versions of quantum cryptography, plus one more that comes into play now we’re dealing with entanglement.

This final problem is the locality loophole: the worry is that there might be some as yet undiscovered signal relaying information between the entangled particles. If there were, that would invalidate our assumptions about randomness and open up the possibility of some genius adversary tapping the signal – although as we’ve seen, that seems like a distant and receding prospect.

←
Turn back to page 24 for more on Bell tests and quantum loopholes

With all the loopholes seemingly closed, quantum theory has passed the test and we know it can be used to create a certifiably safe cryptographic system. There are still a few wrinkles – familiar ones that have always hindered cryptographers. An enemy might break into your office and steal your key, for instance. “Physical security is always an issue,” Mosca says. “If I can look into your lab and see the plain text, then I don’t need to break your cipher.” Makarov points to another caveat: the key distribution might be device-independent, but other parts of the system could be compromised. “You have to trust that no ingredient at the end stations contains some malicious piece,” he says.

Those eternal issues aside, though, we have finally reached the end of the road for perfecting security. It will take time to move from proof of principle to application: implementing the protocol is still hard work for now. In 2015, a team from Delft University of Technology in the Netherlands achieved 245 entanglement events between electrons in diamond (see diagram, left). That's not exactly a useful rate for generating a cryptographic key, which might need to be thousands of digits long, but things are improving. “We expect to be able to make entanglement 100,000 times faster in the near future,” says Henson.

Device independent quantum cryptography, the last word in secret messaging, does now seem to be within our grasp. The quantum part provides an unbreakable protocol; the device-independence takes the reliability of the supplier out of the equation. “In terms of being able to verify physical security, it’s the best,” says Mosca. Ekert agrees: anyone can use the Bell test routine. “You don’t even have to understand physics.” ∎

QUANTUM-PROOF NUMBERS

Practically-minded mathematicians think you might not have to go to all the effort of quantum cryptography – new quantum-proof algorithms could be good enough to protect you online. Crafting them is not for the faint-hearted, though.

NO ONE knows how long it will be before we see a quantum computer with enough qubits, or quantum bits, to crack our most widely-used cryptographic codes. But Michele Mosca of the Institute for Quantum Computing in Waterloo, Canada, has estimated the odds. He reckons there's a 1 in 6 chance that a quantum computer will be able to break RSA and elliptic curve cryptosystems by 2027, and a 1 in 2 chance this will happen by 2031. If he is right, there is at least a 50:50 chance that all our secrets will be exposed before the new standard is established. All of this has moved the US National Security Agency to admit that it "must act now".

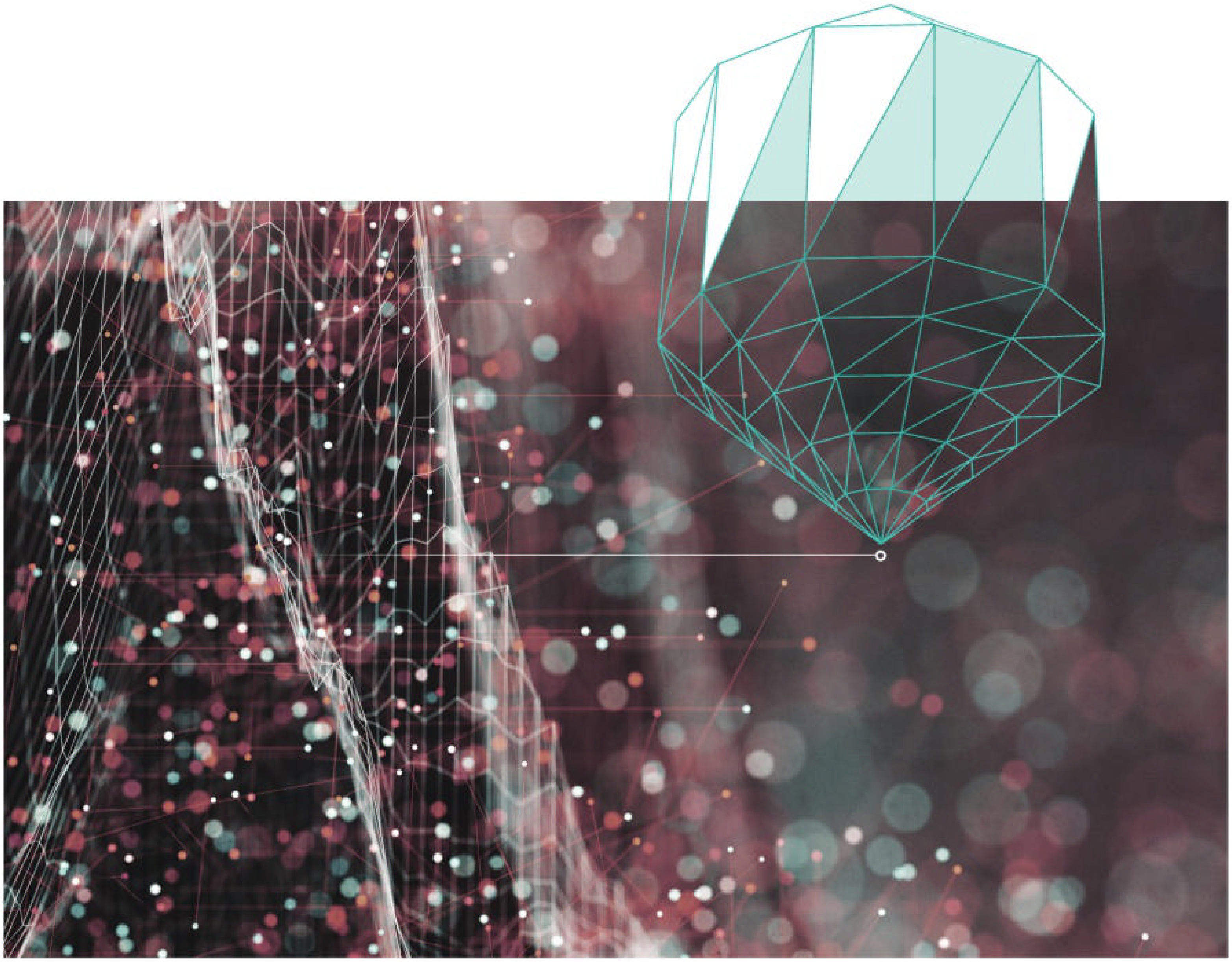
But how? How can anyone expect to design a quantum-computer-proof cryptosystem if we don't yet have a fully functional quantum computer to put it through its paces? Well, we already have a good idea of what these machines will be capable of, so the solution is simple enough to state: you build an algorithm based on mathematics so fiendishly complicated that even a top-notch quantum computer couldn't break it.

Broadly speaking, that will involve one of three strategies. The first, called code-based cryptography, is derived from the tricks that prevent errors creeping into our digital data. All computer systems contain a certain amount of noise, from heat or stray electrical signals, and once in a while this can flip a binary digit from 1 to 0 or vice versa.

Error-correcting codes are designed to spot such anomalous flips, and reverse them. Cryptosystems based on such codes, on the other hand, deliberately put errors in – preferably enough to obscure the message. "If you know how it was constructed, you can remove the errors. But someone who doesn't have that secret key can't decrypt the message," says Dustin Moody, a mathematician in the post-quantum cryptography group of the National Institute for Standards and Technology.

There are also lattice-based cryptosystems, based on navigating through a multidimensional arrangement of points. The security comes from something akin to knowing the shortest route between A and B.

Then there is the multivariate approach, which entrusts its secrets to some of the basics of algebra. It uses equations called quadratic functions, but with lots



GREMLIN/ISTOCK

of different variables. "It turns out that it's really quick to evaluate a quadratic function if you stick in numbers for the variables," says Moody. "However, if someone gives you the answer but doesn't tell you the secret input, it's hard to work backwards and figure out what the input was." That's why the HFEv-signature protocol, which is a multivariate-based cryptosystem, has been unbreakable since its creation in 1996.

We already know – as far as is possible – that these schemes potentially offer quantum-proof encryption because there are only a handful of ways in which a quantum computer can attack the underlying maths, and none of these methods can crack these new schemes. The trouble is that building a working cryptosystem from these mathematical tricks is maddeningly difficult.

As if the maths isn't tricky enough already, it has to be implemented in ways that don't inadvertently introduce weaknesses – bugs that can render the algorithm vulnerable even to classical computers. "Quantum-proof is not the only measure: the classical security is also extremely important," says Lily Chen, a project leader in NIST's cryptographic technology group.

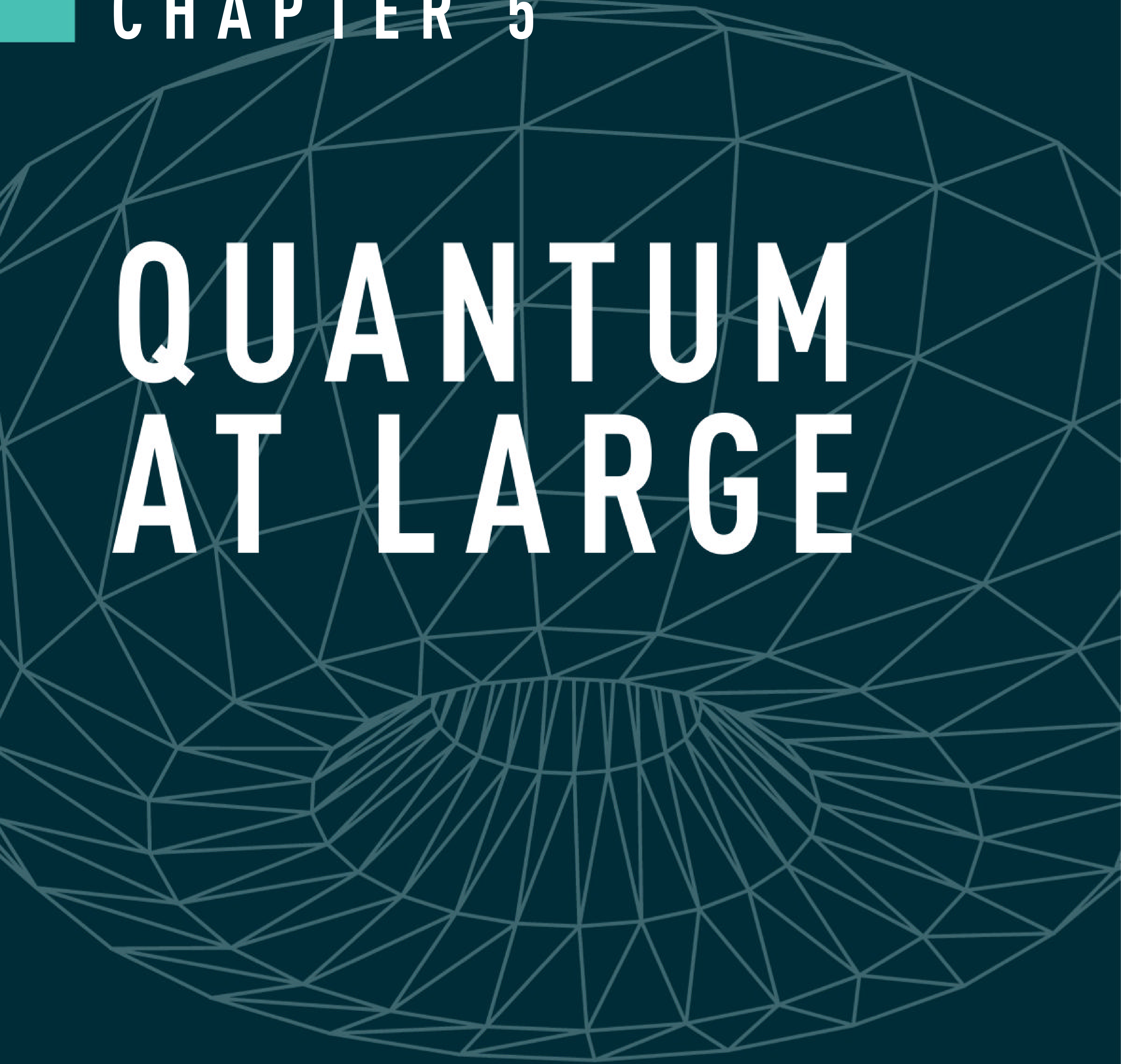
Even if the new algorithms pass all the mathematical tests thrown at them, there's no guarantee that any of them will be truly quantum-proof. Ultimately, there will always be an element of doubt. "We don't know there won't be a new quantum algorithm that works against quantum-resistant cryptography," says Philippe Gaborit at the University of Limoges in France. When we implemented RSA in 1976, he points out, no one could have foreseen Shor's algorithm emerging two decades later. "There is never 100 per cent security."

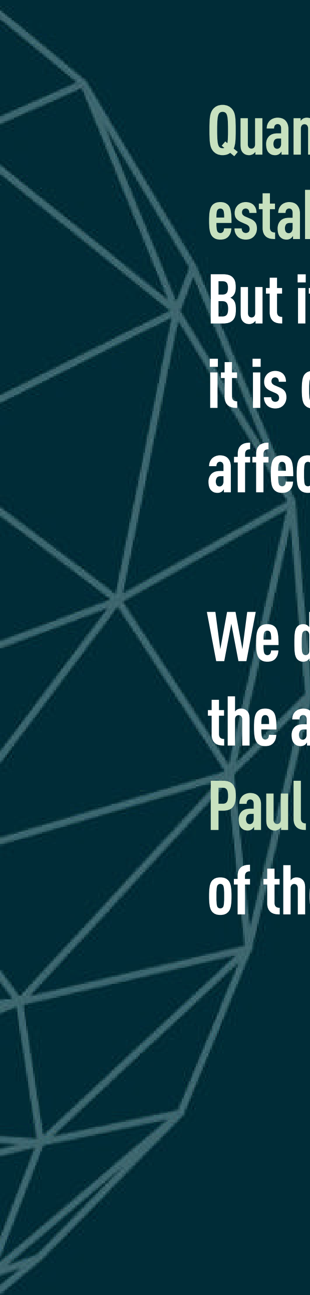
NIST's experts have a positive outlook, nonetheless. Chen is confident that they have the tools needed to create a secure future. "Assessing quantum-proof strength has been a very active research area in recent years," she says. It is now time to put that research to work.

To that end, NIST will select the strongest candidates and encourage everyone involved to sabotage them again. Moody reckons several of them look like they will survive scrutiny – although that might be wishful thinking arising from the widespread eagerness to get to grips with the problem. "We really do want to get something out of this," he says, "because we need to have replacements ready." ■

CHAPTER 5

QUANTUM AT LARGE





Quantum physics rules the domain of the very small, establishing the strange properties of the subatomic world. But its sphere of influence is much larger, it seems. Perhaps it is only right that the fundamental laws of matter also affect the universe that matter inhabits.

We don’t have all the answers yet, but it seems that the arrow of time, the path of evolution and, as physicist Paul Davies explains in our opening essay, even the fate of the universe could be quantum at heart.

THE SECRET LIFE OF EMPTY SPACE

PROFILE
PAUL DAVIES

Paul Davies is a professor of physics at Arizona State University in Tempe. The author of more than 30 books, his research interests span quantum gravity and black holes, the nature of time, the origins of life and the evolution of cancer

MARIO WAGNER

"NATURE abhors a vacuum." This sentiment, which first popped up in Greek philosophy some 2500 years ago, continues to excite debate among scientists and philosophers. The concept of a true void, apart from inducing a queasy feeling, strikes many people as preposterous or even meaningless. If two bodies are separated by nothing, should they not be in contact? How can "emptiness" keep things apart, or have properties such as size or boundaries?

While we continue to struggle with such notions, our idea of the vacuum has moved on. We now know, thanks to quantum theory, that empty space is richer than a mere absence of things – and this richness plays an indispensable part in much of modern physics.

Even among the ancient Greeks, the void divided loyalties. One influential line of thought, first apparent in the work of the philosopher Parmenides in the 5th century BC and today most commonly associated with Aristotle, held that empty space is really filled with an invisible medium. Proponents of the rival atomic theory, among them Leucippus and Democritus, disagreed. In their view, the cosmos consisted of a limitless void populated by tiny indestructible

particles, or atoms, that came together in various combinations to form material objects.

Such metaphysical debates remained standard fare among philosophers into the Middle Ages and beyond. The rise of modern science in the 17th century did little to settle them. Englishman Isaac Newton, like Aristotle, thought that the space between bodies must be filled with a medium, albeit of an unusual sort. It must be invisible, but also frictionless, as Earth ploughs through it on its way round the sun without meeting any resistance.

Newton appealed to this substance as a reference frame for his laws of motion. They predicted, for example, that a spinning planet such as Earth would experience a centrifugal force that would make it bulge at the equator. This effect provided physical proof of the body's rotation, yet such a rotation, and thus the existence of a force, only made sense if there were some absolute frame of rest, a stationary viewpoint against which to compare the motion. This, said Newton, was the invisible medium that filled space.

His German rival Gottfried Leibniz disagreed. He maintained that all motion, including rotation, was only to be judged relative to other bodies in the universe – the distant stars, for example. An observer on a merry-go-round in deep space would see the stars going round and at the same time feel a centrifugal force. According to Leibniz, if the stars were to vanish, so would the force; there was no need for an invisible medium in between.

Leibniz's position was argued forcefully in the 19th century by the German engineer and philosopher Ernst Mach, he of the Mach numbers used in aircraft speed. He proposed that centrifugal forces and related mechanical effects are caused by the gravitational action of distant matter in the universe. Albert Einstein was strongly influenced by Mach's ideas in formulating his theory of relativity, and was disappointed to find that Mach's principle didn't in fact emerge from it. In Einstein's theory, for example, a spinning black hole is predicted to have a bulging waist even when no other object exists.

During the 19th century, the nature of empty space began to occupy the thoughts of physicists in a new context: the mystery of how one charged body feels the pull of another, or how two magnets sense each other's presence. The chemist and physicist Michael Faraday's explanation was that charged or magnetic bodies created regions of influence – fields – around them, which other bodies experienced as a force.

But what, exactly, are these fields? One way physicists of the time liked to explain them was by invoking an invisible medium filling all of space, just as Newton had. Electric and magnetic fields can be described as strains in this medium, like those introduced to a block of rubber when you twist it. The medium became known as the luminiferous aether, or just the ether, and it had an enormous influence on 19th-century science. It was also popular with spiritualists, who liked its ghostliness, and invented obscure notions of "etheric

“Quantum theory says there is an electric field in a box that contains no electric charge”

bodies” said to survive death. When James Clerk Maxwell unified electricity and magnetism in the 1860s, it provided a natural habitat for the rather ghostly electromagnetic waves his theory predicted – things like radio waves and light.

So far, so good. Soon after Maxwell published his theory, however, the old problem of relative motion resurfaced. Even if our planet feels no friction as it slides through the ether, any movement relative to it should still produce measurable effects. Most notably, the speed of light should depend on the speed and direction of Earth’s motion. Attempts to detect this experimentally by comparing the speed of light beams in different directions failed to find any effect.

Einstein came to the rescue. His special theory of relativity, published in 1905, suggests that a body’s motion must always be judged relative to another body, and never to space itself, or space-filling invisible stuff. Electric and magnetic fields exist, but no longer as strains in any space-filling medium. Their strength and direction, and the forces they exert, change with the motion of the observer such that the speed of light is always measured to be the same, independently of how the observer moves. So the ether is an unnecessary complication. While it is true to say that a region of space pervaded by an electric or magnetic field is not empty, the will-o’-the-wisp “stuff” it contains is a far cry from what we normally think of as matter. Fields might possess energy and exert pressure, but they are not made up of anything more substantial.

A decade or so on, however, a new twist cast the problem of empty space in a different light. It emerged from the theory of quantum mechanics. At the level of atoms, the clockwork predictability of the classical, Newtonian universe broke down, to be replaced by a strange alternative set of rules. A particle such as an electron, for example, does not move from A to B along a precisely defined trajectory. At any given moment its position and motion will be, to a degree, uncertain.

What’s true for an electron is true for all physical entities, including fields. An electric field, for instance, fluctuates in intensity and direction as a result of quantum uncertainty, even if the field is zero overall. Imagine a box containing no electric charges – in fact containing nothing but a vacuum – and made of metal so that no electric field can penetrate from the outside. According to quantum mechanics, there will still be an irreducible electric field inside the box, surging sometimes this way, sometimes that. Overall, these fluctuations average out to zero, so a crude measurement may not detect any electrical activity. A careful atomic-level measurement, on the other hand, will.

We now encounter an important point. Although the field strength of the fluctuations averages to zero, the energy does not, because an electric field’s energy is independent of its direction. So how much energy resides in an empty box of a given size? Quick calculations on the basis of quantum theory lead to an apparently nonsensical conclusion: there is no limit. The vacuum is not empty. In fact, it contains an ›

infinite amount of energy.

Physicists have found a way around this conundrum, but only by asking a different question. If you have two metal boxes of different size or shape, what is the difference in their quantum vacuum energy? The answer, it turns out, is tiny. But not so tiny that the difference cannot be measured in the lab, proving once and for all that the quantum fluctuations are real, and not just a crazy theoretical prediction.

So the modern conception of the vacuum is one of a seething ferment of quantum-field activity, with waves surging randomly this way and that. In quantum mechanics, waves also have characteristics of particles, so the quantum vacuum is often depicted as a sea of short-lived particles – photons for the electromagnetic field, gravitons for the gravitational field, and so on – popping out of nowhere and then disappearing again. Wave or particle, what one gets is a picture of the vacuum that is reminiscent, in some respects, of the ether. It does not provide a special frame of rest against which bodies may be said to move, but it does fill all of space and have measurable physical properties such as energy density and pressure.

One of the most studied aspects of the quantum vacuum is its gravitational action. Out there in the cosmos there is a lot of space, all of it presumably chock-full of quantum-vacuum fluctuations. All those particles popping in and out of existence must weigh something. Perhaps that mass is enough to contribute to the total gravitating power of the universe; perhaps, indeed, enough to overwhelm the gravity of ordinary matter.

Finding the answer is a demanding task. We must account not just for electromagnetic fields, but all fields in nature – and we cannot be sure we have all of these pinned down yet. One general result can be readily deduced, however. In the event that the pressure of the quantum vacuum is negative (a negative pressure is a tension), the gravitational effect is also negative. That is, negative-pressure quantum-vacuum fluctuations serve to create a repulsive, or anti-gravitating, force.

Einstein had predicted that empty space would have such an anti-gravitational effect in 1917, before quantum mechanics. He couldn't put a number on the strength of the force, though, and later abandoned the idea. But it never completely went away. Back-of-the-envelope calculations today suggest that the quantum vacuum pressure should indeed be negative in a space that has the geometry of our universe.

Sure enough, evidence began to accumulate from observations of far-off supernovae that a huge anti-gravitational force is causing the entire universe to expand faster and faster. The invisible quantum vacuum "ether" that is presumably at least partially responsible has been restyled as "dark energy". The work that led us to this discovery garnered astrophysicists Saul Perlmutter, Adam Riess and Brian Schmidt a Nobel prize in physics.

While quantum mechanics gives us a way to begin the calculation, a proper understanding of dark energy's strength and properties will probably require new physics, perhaps coming from string theory or some other attempt to bring all the fundamental forces of nature – including gravity, the perennial outsider – under one umbrella.

One thing is clear, however. The notion that space is a mere void with no physical properties is no longer tenable. Nature may abhor an absolute vacuum, but it embraces the quantum vacuum with relish. This is no semantic quibble. Depending on how dark energy works, the universe may continue on a runaway expansion, culminating in a universe of dark emptiness in which matter and radiation are diluted to infinitesimal levels, or it might crush in on itself in a "big crunch". The fate of the universe, it seems, lies in the properties of the vacuum. ■

A QUANTUM OF TIME

Whether you feel the hours ticking by too rapidly or too slowly, it's unlikely that you're prompted to wonder if the quantum properties of the universe are to blame. But these might offer our best hope of explaining just what it is that moves the hands of time.

A CENTURY ago, Einstein's theories of relativity revolutionised our ideas of time. They gave it a physical identity as part of space-time, a malleable fabric on which reality's events play out.

Einstein's ideas are mathematically sound and, as with the predictions of quantum theory, have been rigorously confirmed by experiments, but moulding together space and time as if they were the same thing doesn't square with our experience. True, both space and time separate objects and events. But we are free to move as we please in space, at least in theory. Time, on the other hand, dictates a direction of travel, trapping us in an eternal present as it conveys us from the past to the future.

If this flowing time is not contained within our fundamental description, where does it come from? Maybe from the quantum world.

In the equations of quantum theory, time is not a dynamic, malleable component of the fabric of the universe, as it is in relativity. It is something much closer to the way we intuitively think of it, as a steady beat of a clock that sits somewhere outside the universe, against which the processes of reality play out.

Perhaps, then, we have things backwards, and particles create time rather than being ruled by it. In 1972, the French mathematician Alain Connes discovered a quantum version of time in algebra the polymath John von Neumann had developed in the 1930s to explore quantum theory – and promptly forgot about it. "I did not know what role it could have in physics and how it could relate to the classical notion of time," says Connes.

In 1994, he bumped into Carlo Rovelli in Cambridge, UK. Rovelli, who works at Aix-Marseille University in France, had just written two papers about the role of time in theories that seek to unite relativity and quantum theory. Rovelli's ideas matched up with Connes's quantum time, and they began to collaborate.

The core of the argument they have developed is that time's arrow emerges from interactions between microscopic quantum objects – atoms, photons of light and the like – and macroscopic classical objects that "measure" those objects' properties. Measurement is hugely important in the quantum world. Before a measurement, we have only probabilities concerning the position or momentum, say, of a quantum object. Only afterwards does uncertainty collapse into classical certainty. ›

←
Chapter 3 has a full discussion of quantum interpretations and the measurement problem

Except it doesn't, quite. Heisenberg's quantum uncertainty principle states that our knowledge of the quantum world is limited even after measurement. The more precisely we know one property, such as position, the more limited we are in determining another, such as momentum. Since all measurement outcomes are probabilistic, varying from case to case, the order in which we make measurements determines their outcome. "The true variability underlying physics is not the passing of time, but the 'non-reproducibility' of the outcome of quantum experiments," says Connes.

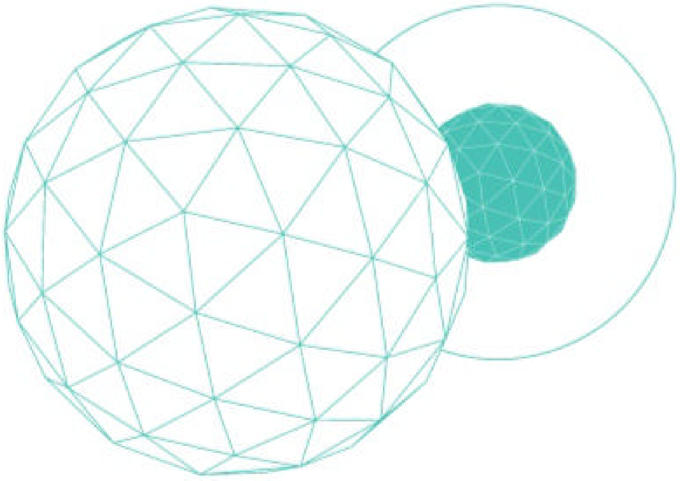
←
Turn back to page 10 for more on the uncertainty principle

That would mean that time isn't fundamental. There is no order of time in the quantum world; temporal order appears only when processes such as measurement irreversibly turn quantum phenomena into observable classical phenomena. Applied to thermal systems, what emerges matches the second law of thermodynamics – the relentless rise of disorder, or entropy, in the universe, that many physicists associate with the passage of time. "The flow has the same properties as what we call time," says Rovelli.

In this picture we have, in effect, reverse-engineered equations that contain the kind of time we think we see, without it ever really being there. Rovelli calls it a "perspectival origin of time", an illusion that results from limited information – our own ignorance. It is as if we only ever saw light through a polarising filter, and so concluded that all light was polarised in one direction. "We are little things, even with all our telescopes and microscopes," says Rovelli. "We interact with an extremely minute part of the universe. There might be entire domains of it we don't yet know about." ∎

IS LIFE QUANTUM?

It may be navel-gazing, but it's fair enough to wonder whether the quantum nature of the atoms that make up your body has any influence over your behaviour. It's a question that physicists have been keen to answer for decades now – and they are finally turning up some intriguing clues as to the connections between the quantum and the living worlds.



WE TEND to think that the interaction between quantum physics and biology stops with Schrödinger's cat. Not, as we've seen, that Erwin Schrödinger intended his unfortunate feline, suspended thanks to quantum rules in a simultaneous state of being both dead and alive, to be anything more than an absurd metaphor. When he wrote his 1944 book *What is Life?*, he speculated that living organisms would do everything they could to block out the fuzziness of quantum physics.

But is that the case? On one level, you might think, we shouldn't be surprised if life has a quantum edge. After all, biology is based on chemistry, and chemistry is all about the doings of atomic electrons – and electrons are quantum-mechanical beasts at heart. That's true, says quantum physicist Jennifer Brookes, who now researches at firm called, appropriately enough, Schrödinger. "Of course everything is ultimately quantum because electron interactions are quantised."

On another level, it is gobsmacking. In theory, quantum states are delicate beasts, easily disturbed and destroyed by interaction with their surroundings. So far, physicists have managed to produce and manipulate them only in highly controlled environments at temperatures close to absolute zero, and then only for fractions of a second. Finding quantum effects in the big, wet and warm world of biology is like having to take them into account in a grand engineering project, says Brookes. "How useful is it to know what electrons are doing when you're trying to build an aeroplane?" she asks.

Might this received wisdom be wrong? Take smell, Brookes's area of interest. For decades, the line has been that a chemical's scent is determined by molecular shape. Olfactory receptors in the nose are like locks opened only with the right key; when that key docks, it triggers nerve signals that the brain interprets as a particular smell.

Is that plausible? We have around 400 differently shaped smell receptors, but can recognise around 100,000 smells, implying some nifty computation to combine signals from different receptors and process them into distinct smells. Then again, that's just the sort of thing our brains are good at. A more damning criticism is that some chemicals smell similar but look very different, while others have the same shape but smell different. The organic compounds vanillin and isovanillin, for example, smell differently but are two similarly shaped arrangements of the same molecule.

There is an alternative explanation. Around 70 years ago, even before the lock-and-key mechanism was suggested, the distinguished British chemist Malcolm Dyson suggested that, just as the brain constructs colours from different vibrational frequencies of light radiation, it interprets the characteristic frequencies at which certain molecules vibrate as a catalogue of smells.

The idea languished in obscurity until 1996, when Luca Turin, a biophysicist then at University College London, proposed a mechanism that might make vibrational sensing work: electron tunnelling. This phenomenon results from the basic fuzziness of quantum mechanics, and is a staple of devices from microchips to microscopes. When an electron is confined in an atom, it does not have an exactly defined energy but has a spread of possible energies. That means there is a certain probability that it will simply burrow through the energy barrier that would normally prevent it escaping the atom. ›

Turin's idea is that when an odorous molecule lodges in the pocket of a receptor, an electron can burrow right through that molecule from one side to the other, unleashing a cascade of signals on the other side that the brain interprets as a smell. That can only happen if there is an exact match between the electron's quantised energy level and the odorant's natural vibrational frequency. "The electron can only move when all the conditions are met," Turin says. The advantage, though, is that it creates a smell without the need for an exact shape fit.

It was a controversial notion. In 2007 Brookes, then also working at University College London, and colleagues showed that the mechanism is physically plausible: the timescales are consistent with the speed with which the brain responds to smell, and the signals generated are large enough for the brain to process. And Turin, now at the Alexander Fleming Biomedical Sciences Research Centre in Vari, Greece, and his colleagues have delivered what looks like evidence for vibrational sensing. They showed that fruit flies can distinguish between two types of acetophenone, a common base for perfumes, when one contains normal hydrogen and the other contains heavier deuterium. Both forms have the same shape, but vibrate at different frequencies. That sensitivity can only mean electron tunnelling, says Andrew Horsfield of Imperial College London, a co-author on Brookes's paper: in classical models of electron flow the electron would not be sensitive to the vibrational frequency. "You can't explain it without the quantum aspect."

Smell is not the only thing that proponents of quantum biology think it might explain: there's also the mechanism that powers the entire animal kingdom. We all run on adenosine triphosphate, or ATP, a chemical made in cells' mitochondria by moving electrons through a chain of intermediate molecules. When we attempt to calculate how speedily this happens, we hit a problem. "In nature the process is much faster than it should be," says Vlatko Vedral, a quantum physicist at the University of Oxford.

Vedral thinks this is because it depends on the quality of "superposition" which allows the sort of quantum-mechanical wave that describes electrons to be in two places at once. He reckons quantum omnipresence might speed the electrons' passage through the reaction chain. "If you could show superposition is there and it's somehow also important for the electron flow, that would be very interesting," he says.

Vedral's first calculations support the idea, but he says it is too early to make any claims. It is hard to estimate all the parameters involved in electron transport, and it is possible that the classical calculations just used the wrong numbers. "And as yet we have no experimental proof," he says. Such proof might be quite close by – in how plants and some bacteria get their energy. It seems photosynthesis might be very much a quantum game.

Direct evidence that this is so came in 2007, when a group led by Graham Fleming at the University of California, Berkeley, took a close look at photosynthesis in the green sulphur bacterium *Chlorobium tepidum*. They detected "beating" signals characteristic of quantum wave interference in the photosynthesising centres of bacteria cooled to 77 kelvin. Then in 2010 a group led by Gregory Scholes of the University of Toronto, Canada, showed a similar effect at room temperature in light-harvesting proteins from two marine algae.

This is a trick we might like to learn from. Although photosynthesis is not particularly efficient overall, the initial stage of converting incoming photons into the energy of electrons within a photosynthesising organism's light-gathering pigment molecules is extremely effective. When sunlight is weak, plants are able to translate more than 90 per cent of photons into an energy-carrying electron; in strong sunlight plants have to dump about half the energy to avoid overheating.

Scholes's explanation for this is that when sunlight hits electrons, they are kicked into a quantum superposition that allows them to be in two places at once. That effectively "wires" light-gathering molecules to the reaction centre where the photosynthesis takes place for a few hundred femtoseconds. During that time, an electron can, according to quantum rules, take all paths between the two places simultaneously. Probing the process more closely causes the superposition to collapse – and reveals the electron to have taken the path that lost it the least energy.

Might we take a leaf out of biology's book? Scholes thinks so. "Every year there are thousands of papers published on energy transfer," he says. "It sounds harsh but we haven't learned a thing apart from the obvious." A better understanding of what is going on might also help us on the way to building a quantum computer that exploits coherent states to do myriad calculations at once. Efforts to do so have so far been stymied by our inability to maintain the required coherence for long – even at temperatures close to absolute zero and in isolated experimental set-ups where disturbances from the outside world are minimised.

This remains the central conundrum for the physicists studying quantum aspects of biology. If we can't do these things in our isolated labs, how can a leaf in your less-than-isolated garden do it? If only the European robin could do more than warble chirpily. Perhaps then it could tell us – and explain its own apparent quantum superpowers, too.

In 2004, Thorsten Ritz of the University of California, Irvine, showed how magnetic disturbances that would only show up on systems that could detect transitions between particular quantum-mechanical atomic spin states could disrupt the compass of the European robin, *Erithacus rubecula*.

Ritz suggested that birds come equipped with a sensor system containing spin states that flip in response to changes in Earth's magnetic field, producing signals that the bird's brain in some way detects. But how?

The first proposal was that some apparatus in the eye initiates a chemical response. But this would require a constant, fast flipping of spins to keep chemical information flowing, whereas the birds seemed to maintain delicate spin states for extraordinarily long times of up to 100 microseconds.

According to the late Marshall Stoneham of University College London and his colleagues, the problem might be overcome if the birds used something similar to a human visual peculiarity that detects light polarisation. Known as Haidinger's brush, this superimposes a faint, yellow bow-tie shape on our visual field, and is thought to result from the way blue light-absorbing lutein molecules are arranged in concentric circles within our eye. Stare at a blank piece of paper and a polarising filter or a blank document on a laptop screen and you can see it for yourself.

Stoneham calculated that a magnetic field could produce a similar distortion in a bird's visual field, the orientation of which would change with a change in magnetic field. Crucially, that would occur only if quantum states lasted long enough to affect many of the bird's light sensing molecules at the same time. Birds might see the result, Stoneham suggested, in a kind of a head-up display of the kind that is embedded in the windscreens of some luxury cars.

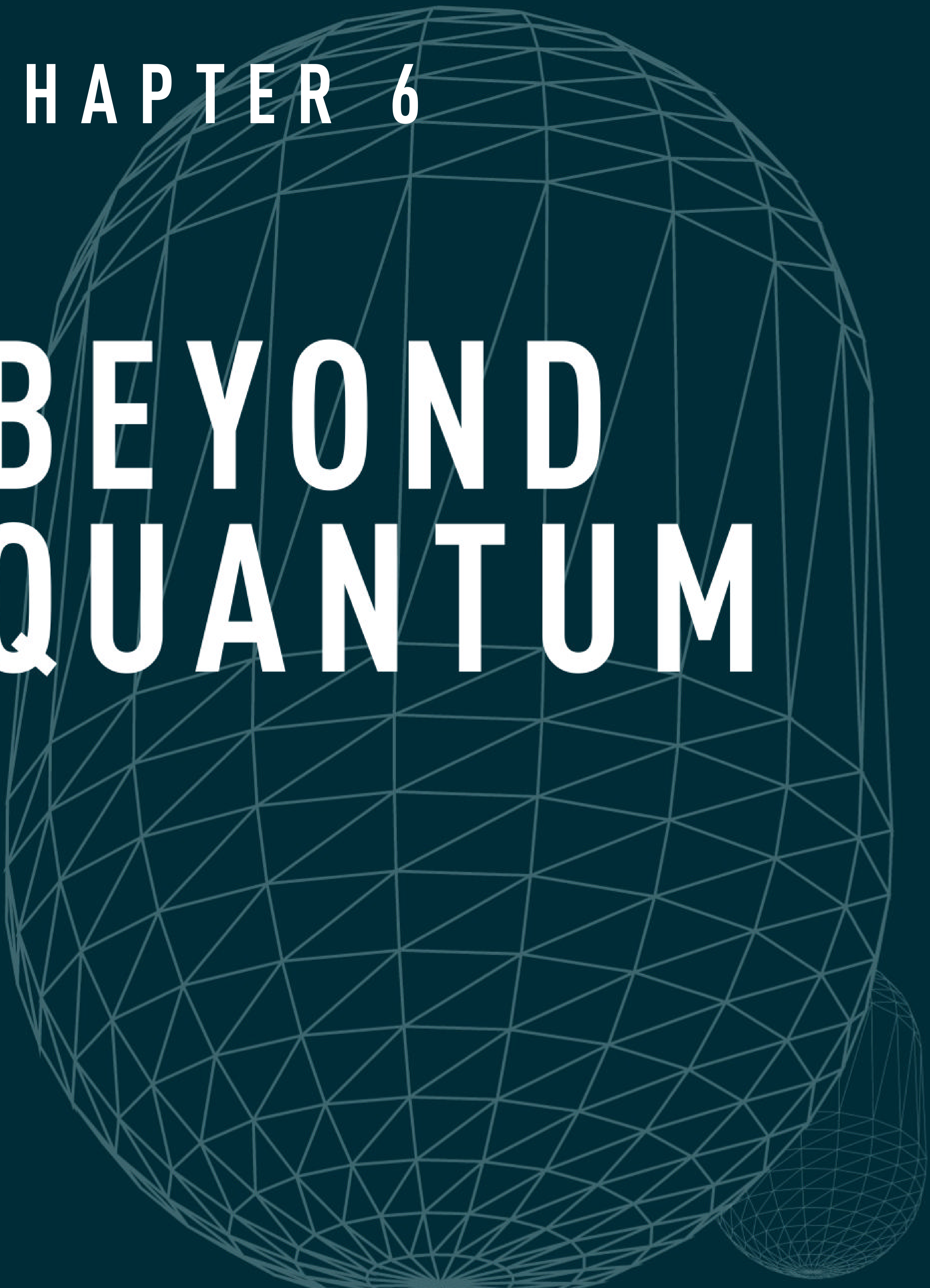
At the moment we still have little more than educated guesses about whether evolution has really harnessed quantum effects. Scholes thinks that proteins around algae's light-harvesting equipment might have evolved structures that shield disturbances from the environment and so allow processes within to exploit the magic of quantum physics to give them a selective advantage. Vedral thinks something similar, although why and how nature would do this, he says, is "completely unclear".

Turin shrugs his shoulders, too. "Life's 4 billion years of nanoscale R&D will have engineered many miracles," he says. We should learn to accept what we see and try to mimic it, he says – and not just in solar cells and quantum computers. While what makes a drug effective or ineffective is far from clear, for instance, we do know that the operation of things like neurotransmitters in our brains depends on redox reactions, which are all to do with electron flow. If those flows occur in weirder ways than we have hitherto imagined, that could open up a new path to design drugs to treat some of our most pernicious ailments.

All those stepping gingerly around this new field agree that caution is needed – yet there is a palpable sense of excitement. Max Planck first discovered quantum theory more than a century ago because of odd observations about electromagnetic radiation that could be explained in no other way. That led to the laser and the semiconductor and all the technological revolutions they have seeded. Quantum biology is at that early stage of inexplicable observations, but Turin for one believes something big is emerging. "I can't help thinking we are seeing just a small part of a far, far bigger iceberg," he says. ∎

CHAPTER 6

BEYOND QUANTUM



Quantum mechanics is the most successful theory of material reality we have ever had. Yet many physicists are convinced it can't be the final answer.

That's not least because of how the theory fails to mesh with general relativity, Einstein's equally peerless theory of gravity. In this final chapter, two prominent physicists give their take on this unresolved conundrum – Sean Carroll and, first, Lee Smolin.

A MANIFESTO FOR A NEW REALITY

QUANTUM mechanics is often called a theory of the very small. In reality, it explains phenomena on a vast range of scales – from elementary particles and their interactions, through atoms and molecules, all the way to neutron stars and the supernovae that spawn them. So far, essentially all its predictions have been confirmed by experiments. It is the most successful theory of material reality we have ever had.

So why have so many physicists, from Albert Einstein onwards, taken the view that quantum theory is wrong?

The reasons lie in its mysterious nature, in the phenomena it doesn't explain and the answers it doesn't give. That is reason enough to seek what might lie beyond it. I believe we already have the outline of what this deeper answer looks like

We are only at the start of this work, but by digging down into the fundamental principles that underlie reality, and weeding out what is right and what is wrong about our current ideas, we can see glimpses of a truly unifying picture of physics. It comes at a price: to go beyond quantum, we must totally upend long-held ideas of how the universe hangs together.

Einstein wasn't the only quantum pioneer to express doubts about quantum theory. Louis de Broglie, who

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PROFILE
LEE SMOLIN

Lee Smolin is a theoretical physicist at the Perimeter Institute in Waterloo, Canada, and the author of *Einstein's Unfinished Revolution: The search for what lies beyond the quantum*

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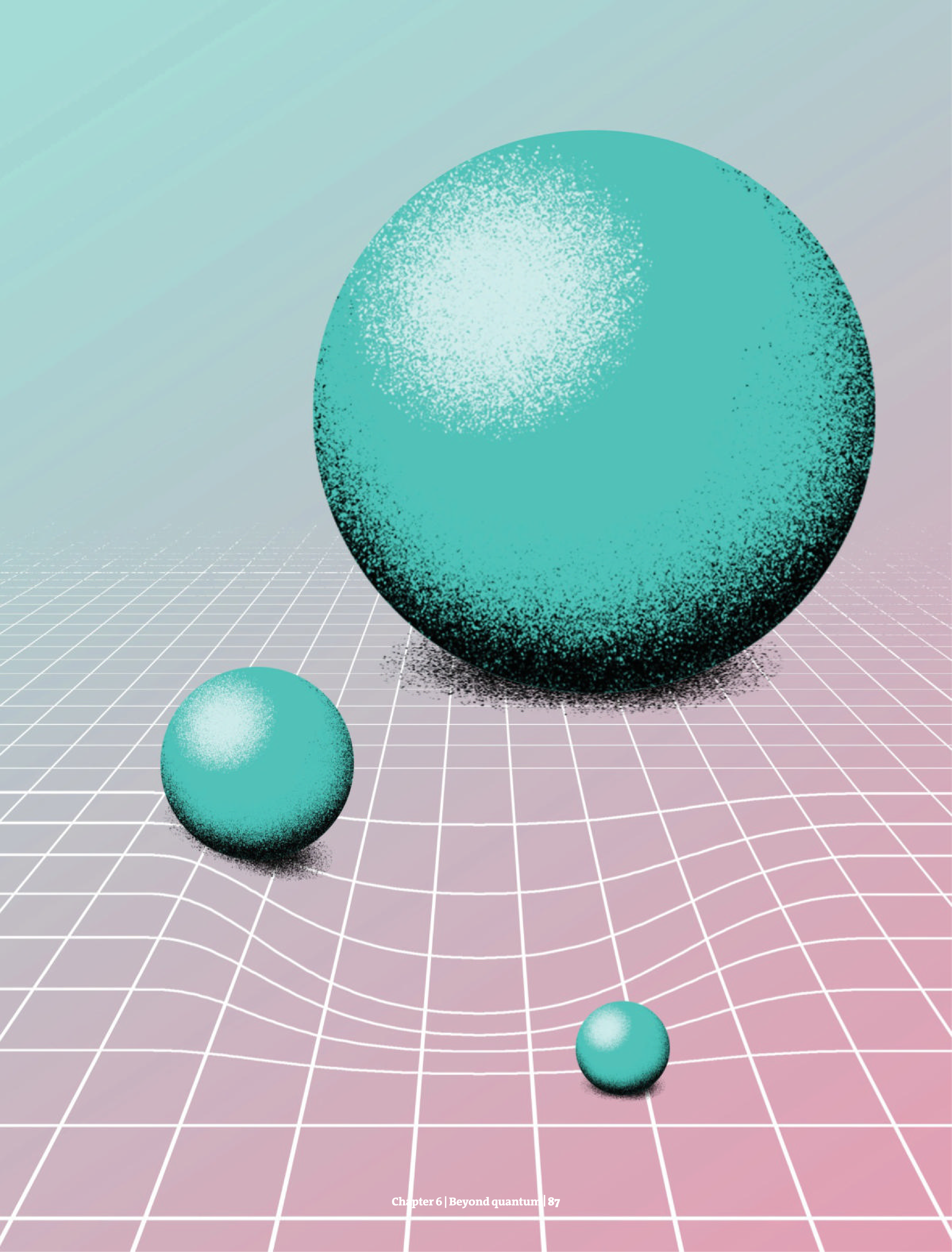

first predicted the wave-like aspects of matter, was another sceptic, as was Erwin Schrödinger, whose famous thought experiment of the dead-and-alive cat was designed to highlight the absurdity of quantum theory's prediction of alternative realities. In the present day, quantum dissidents include the Nobel-prizewinning theorists Roger Penrose and Gerard 't Hooft.

Arguments about whether quantum mechanics is a complete theory of reality have usually been carried out in isolation. But the route to a deeper and truer understanding of nature may lie in connecting the problems of quantum theory with other big, open problems in fundamental physics.

The most obvious one is how to develop a quantum theory of gravity. Gravity is the only one of nature's four fundamental forces not to have a quantum-mechanical description. It is described by Einstein's general theory of relativity as an effect resulting from massive objects warping space-time around them.

General relativity and quantum theory seem to be fundamentally incompatible, not least in the way the former describes a smooth, malleable space-time. By contrast, quantum theory suggests that it must at some level come in discrete chunks, or quanta, of space or space-time.

We have at least half a dozen ways to get part of the way across this divide, among them string theory and loop quantum gravity. Indeed, the latter idea gives precise predictions for what the quanta of space-time must look like. But we have no idea whether any of the suggested routes are the right one because none predicts an experimental test we can perform with current technology.

Quantum theory and general relativity clash in other ways, too, notably over the nature of time. Relativity makes it impossible to establish one objective "flow" of time of the sort we perceive, with a past and a future separated by a universally defined now. Quantum theory, meanwhile, characterises time as a metronomic "beat" set somewhere outside the universe. So is our perception of a flowing time real, or an illusion?

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Turn back to page 79 for more on the quantum nature of time

There are other deep questions. The quantum descriptions of the other three fundamental forces – electromagnetism and the weak and strong nuclear forces – can be bundled together into the so-called standard model of particle physics. But why do these three forces have such very different strengths within the standard model? Then there is the nature of the dark matter and dark energy that dominate the cosmos on a large scale, but which the standard model doesn't mention. These questions and others concern how our universe came to be, out of a vast number of seemingly equally probable universes allowed by the laws of physics.

To solve all these issues, we need to wipe the slate clean, go back to the first principles of quantum theory and general relativity, decide which are necessary and which are open to question, and see what new principles we might need. Do that, and an alternative description of physics becomes possible, one that

THE SMOLIN MANIFESTO: THE MAIN POINTS

Six hypotheses are needed to begin to rewrite physics with causation at its core, and perhaps solve the problem of uniting quantum theory and relativity.

1. The history of the universe consists of events
2. Time causation is fundamental
3. Causation doesn't go backwards: events don't "unhappen"
4. Space is constructed from the web of causation between events
5. Energy and momentum are conserved when events cause other events
6. The amount of information that can flow between events through emerging space is determined by that space's area

explains things not in terms of objects situated in a pre-existing space, as we do now, but in terms of events and the relationships between them.

This endeavour starts with a few basic hypotheses about the nature of space and time. First, that the history of the universe consists of events and the relationships between them. Second, that time – in the sense of causation, the process by which future events are produced from present events – is fundamental. Third, that time is irreversible: causation can't go backwards, and once an event has happened, it can't be made to unhappen. Fourth, that space emerges from this description: events cause other events, creating a network of causal relationships. The geometry of space-time arises as a coarse-grained and approximate description of this network.

A fifth hypothesis is that energy and momentum are fundamental features of the universe, and are conserved in causal processes. These five hypotheses define a class of models called energetic causal set models that my collaborator Marina Cortês of the Royal Observatory in Edinburgh, UK, and I introduced in 2013. I have since added a sixth hypothesis, a version of the holographic principle first stated by 't Hooft. This says that when two-dimensional surfaces are defined in the emerging geometry of space-time, their area gives the maximum rate by which information can flow through them.

In this picture, every event is distinguished by the information available to it about its causal past. We call this the event's sky because it functions rather like the sky above us does. The sky – or the horizon of our sight more generally – is a snapshot of what we see at any one instant, a two-dimensional surface formed by photons of different colours, informing us of our relationships with the things around us. Because nothing travels faster than the speed of light, only things within an event's sky can influence it, so the sky is also a view of its causal past.

This picture allows us to describe how information and energy flow through events as the universe evolves. Ted Jacobson at the University of Maryland in the US and Thanu Padmanabhan at the Inter-University Centre for Astronomy and Astrophysics in Pune, India, have independently shown that the sixth hypothesis, together with the first law of thermodynamics, which governs the amount of useful energy available to a process, can be used to derive the equations of general relativity, and hence gravity.

Their work assumes that space-time is always smooth. By marrying their reasoning with the picture of a prototypical discrete, quantum space-time in our models, we can derive both general relativity and smooth space-time as emerging from a dynamically evolving causal network.

As well as providing the seed of a quantum picture of gravity, this immediately solves the problem of the flow of time in Einstein's cosmos. In a causally defined universe, the most basic interaction is the creation of an event when two "parent" events come together to make something new happen. At each stage in the construction of a space-time history, the future doesn't exist. But we can postulate a limit to the number of events any parent event can give birth to. Events that have had their full allotment of progeny cannot have any further direct influence on the future, and are

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relegated to the past: time flows.

The most exciting prospect, which Cortês and I have been exploring over the past few years, is that quantum theory might also emerge from this picture. That comes from building energetic causal set models to answer the key question of which events interact.

Events differ from one another in that each has a different sky, a different view of its causal past. We can define a measure of how similar two events' views are, and pick the pair with the most similar views to be the parents of the next event. The idea is that the similarity of views can play the role that distance in space does in conventional classical and relativistic physics. The more similar the views of two events, the more likely they are to interact.

The overall effect of choosing the pair with the most similar views as parents pushes both out of the present and into the past. Removing two very similar views and creating a new view that is a synthesis of both – and hence different from both – has the effect of increasing the total diversity of the views of all events in the universe. A measure of the total diversity of an ensemble of views is a quantity we invented in the late 1980s with Julian Barbour at the University of Oxford. We called it the variety of the system.

All this has intriguing consequences. The views are chosen and evolve precisely so that the total variety evolves to its maximum – and it turns out that this exactly reproduces the dynamics of quantum theory.

You can begin to see how this works. Similarity of views only implies nearness in emergent space-time for large, complex events. If an event has a very simple recent causal past, there may be other simple events with similar pasts that aren't necessarily nearby in the emergent space-time. Yet by the principle of similarity, they have a high probability of interacting with each other.

Einstein and others since have proposed that quantum wave functions describe collections, or "ensembles", of systems defined by properties they share, but it has never been clear whether these ensembles truly exist. In this "real ensemble" picture, they do. The continual, brazenly non-local interactions between simple, causally related objects widely distributed in space explain all the probabilities, uncertainties and spooky interactions of quantum physics. They only ever occur between simple systems such as single particles on a microscopic scale because only these can have similar views. Large, complex systems with many degrees of freedom – you, me, Schrödinger's cat – will have a unique causal past. For us, the closer we are in space or space-time, the more similar our view will be. Proximity matters at the classical scale in a way it doesn't at a quantum scale.

In a series of papers, my collaborators and I have also shown how to describe an interaction among the members of each ensemble that results in the ensemble's quantum state evolving in time according to the laws specified in quantum mechanics. That gives a simple and elegant solution to the measurement problem.

There remains the question of what happens with systems of an intermediate size, whose causal pasts aren't unique, but which might have an intermediate degree of causal relationship with things far away in space. These, I predict, should be described by a tweaked version of quantum physics in which the superposition principle fails to hold exactly. It is possible that experimentalists can construct such systems, and test this prediction, using the tools of quantum information. If we can create sufficiently large and complex entangled states, which would have no or only a few natural copies within the universe, our picture predicts that their evolution in time will deviate from that predicted by quantum mechanics.

More details need to be filled in. This is just a sketch of how we might go beyond today's quantum picture and construct a unified physics that sidesteps the fundamental problems we currently see ourselves facing, while preserving the best of what we have. No doubt it isn't correct in every detail, and others may come along with other, entirely different ideas. But the current impasse in physics suggests that it is only through bold ideas that we will move forward. ▮

WEIRDER THAN WEIRD?

The different perspectives in this chapter suggest either that quantum principles must be rewritten to accommodate general relativity, or that the fabric of that theory, space-time, is itself a quantum invention. Or there might be a third option: that our best theory of reality is just a fuzzy version of something bigger.

ONE glaring incompatibility between quantum theory and general relativity concerns black holes, entities whose gravitational attraction is so strong that not even light can escape their pull. If you throw a quantum particle into one, information about its properties simply disappears. This is deeply weird: ordinarily, any missing information in quantum mechanics can always be found by expanding your viewpoint.

Think of it as a missing set of keys: they are never really missing, only being searched for in the wrong places. Information about the physical properties of a particle lost to a black hole, however, can't be found anywhere – even if you include the whole universe in your search. This black hole information paradox has bothered many great physicists, including Stephen Hawking.

The trouble doesn't end there. Take causality, the cherished notion that cause always precedes effect. You may think this principle applies at all times and places throughout the universe. Instead, general relativity grants every observer their own notion of present and future, so it allows different people to disagree about the causal ordering of certain events.

In contrast, quantum mechanics says that events occur in a fixed causal order that different observers always agree on. To accommodate these conflicting ideas, whatever theory lies beyond quantum mechanics must allow for our notions of causality to get very funky indeed.

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See page 30 for a discussion of the idea of retrocausality in quantum theory

In the last decade or so researchers like Lucien Hardy at the Perimeter Institute for Theoretical Physics in Canada have been pushing the limits of quantum mechanics. By tweaking our standard notions, they have come up with a landscape of fresh theories that – at first sight – may not correspond to our physical reality, but do maintain some of the hallmarks of quantumness and allow a rigorous investigation of possible post-quantum theories. John Selby at the Perimeter Institute and Ciarán Gilligan-Lee, then of University College London, found that a theory that reduces to quantum mechanics – in the same way as quantum mechanics reduces to classical physics – must either abandon the concept of causality, or the notion that information is conserved, or both.

Although quantum mechanics is often regarded as weird, in its standard conception at least it had left untouched these two fundamental prejudices of ours about the natural world. Now it turns out that to find a better theory of reality, we need to look for the weirdness that quantum mechanics didn't predict at all. The clouds on the horizon of quantum physics could be the harbingers of its eventual replacement.

Work done in the early 90s by Rafael Sorkin, a quantum gravity researcher now based at the Perimeter Institute, has helped us shed light on what such a replacement could look like. Sorkin considered one of the benchmark tests in quantum physics, the double-slit experiment, in which particles are fired one by one at a screen through a barrier with two slits. According to common sense, at the end of the experiment there should be only two slit-like marks on the screen, one for each opening the particles could have gone through. This doesn't happen: quantum interference causes a pattern to appear, as though the stream of particles was behaving like a barrage of waves.

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Turn back to page 13 for the lowdown on the double-slit experiment

Sorkin calculated that when you add a third slit to the barrier, quantum mechanics would predict an interference pattern that looks like the patterns for each possible two-slit combination laid over one another. In other words, no new mysterious effects emerge in the three-slit case that aren't present in the two-slit one, although the reason for this is unclear. So far, experiments have put bounds on how big any hypothetical effects could be, but haven't been able to rule them out – yet.

Further research has shown that any such effects must violate information conservation. In other words, they could be a hallmark of any future post-quantum theory. So just as the double-slit experiment first showed us the hallmarks of quantum weirdness, so the triple-slit experiment could take us beyond it. Of course, the jury is still out on the specific form such a theory would take. But one thing's for sure: if you think quantum mechanics is weird, you ain't seen nothing yet. ■

Space-time is the warp and weft of reality, but what is it made of itself? A bold new perspective suggests space-time might emerge from quantum entanglement, says Sean Carroll

WEAVING REALITY'S FABRIC

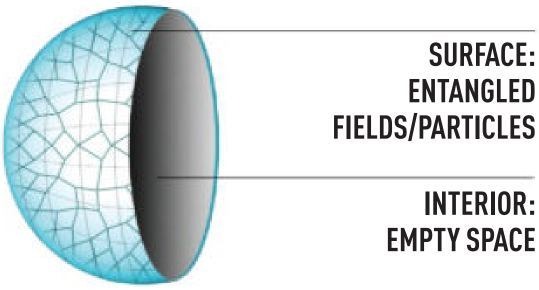
PROFILE
SEAN CARROLL

Sean Carroll is a physicist at the California Institute of Technology and the author of *Something Deeply Hidden: Quantum worlds and the emergence of space-time*

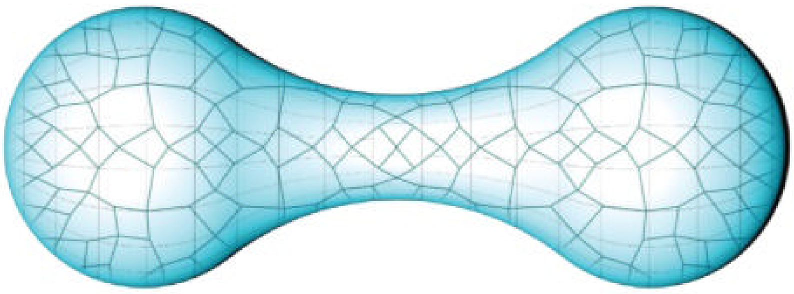
"SPACE-TIME" is simply the physical universe inside which we and everything else exists. And yet, even after millennia living in it, we still don't know what space-time actually is. Physicists have strived to work it out for more than a century. In recent years, many of us have been trying to figure out what might be the threads from which the fabric of reality is woven. We have ideas, each with its own selling points and shortcomings. But for my money, the most exciting one is the most surprising.

It is the idea that space-time emerges from a weird property of the quantum world that means particles and fields, those fundamental constituents of nature, can be connected even if they are at opposite ends of the universe. If that is correct, we might finally have found a bridge between the two irreconcilable totems of physics, placing us on the threshold of a theory of quantum gravity. We would also have the most startling demonstration yet that the world we see isn't the world as it is – that there is always "something deeply hidden", as Albert Einstein put it – and that the only way to understand the fundamental nature of reality is by confronting quantum mechanics head-on.

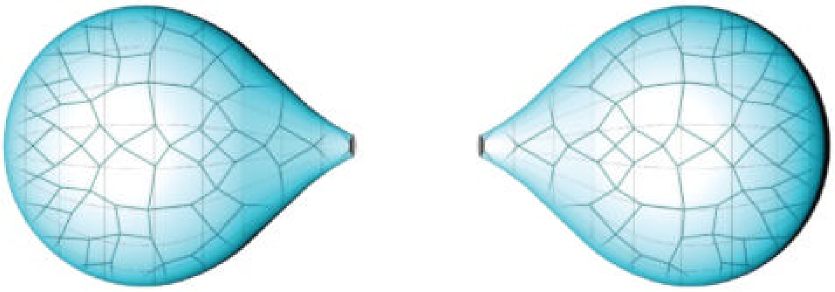
Space-time is a relatively new notion. Isaac Newton had no need for it. For him, space and time were individually real and absolute. Only when Einstein formulated his special theory of relativity in 1905 did the two start to come together. He showed that different observers will generally divide space-time into "space" and "time" in different, incompatible ways; what is "space" and what is "time" are relative to how an observer is moving.



In a model universe, the equations describing gravity in a volume of space are equivalent to those describing the surface of that volume, which don't include gravity. This suggests space on the inside somehow emerges from the properties of the outside, namely entanglement



Sure enough, when you reduce the entanglement connecting two regions of the outside surface, the space inside pulls apart as if pulling at two ends of a piece of chewing gum



If you eliminate all entanglement, the space inside splits in two, suggesting that entanglement is the thread that binds space-time

Various thinkers had previously speculated that the two should be rolled together. In Edgar Allan Poe's 1848 prose poem Eureka, for instance, he wrote that "space and duration are one." But it wasn't until 1908 that mathematician Hermann Minkowski unified them in a scientific way. He dramatically proclaimed: "Henceforth, space for itself, and time for itself, shall completely reduce to a mere shadow, and only some sort of union of the two shall preserve independence."

Einstein was unimpressed, grumbling about "superfluous learnedness". But he eventually came round to the idea, putting the geometry of space-time firmly at the heart of his general relativity. It said that space-time isn't merely a static background in which things happen. It is a dynamic entity, warping and stretching under the influence of mass and energy. The curvature of space-time manifests itself to us as the force of gravity.

Still, it would seem weird to ask what space-time is "made of" in classical physics. In general relativity, space-time changes over time in response to other stuff. But it is still a background, and a fundamental constituent of nature. It isn't made of anything; it just "is".

The problems with that view started with the discovery of quantum mechanics. Scientists haven't been able to construct a quantum-mechanical theory of gravity as they have for the three other fundamental forces of nature. Part of the issue is technical: when we try to make classical general relativity into a quantum-mechanical theory using standard techniques, our equations blow up and we get nonsensical answers. But part of it is conceptual.

Quantum mechanics tells us that systems exist in superpositions of different measurable quantities like position and velocity. There is no such thing as "the position" of a quantum particle; there are many possible positions, which take on definite values only when we observe them. How in the world can space-time exist in a superposition of different possibilities? That would make it impossible to say for sure that a certain event happened at a definite location in space and time.

Physicists of different persuasions have taken different approaches to constructing a solution in the form of a theory of quantum gravity. The most popular is string theory, which replaces particles with loops

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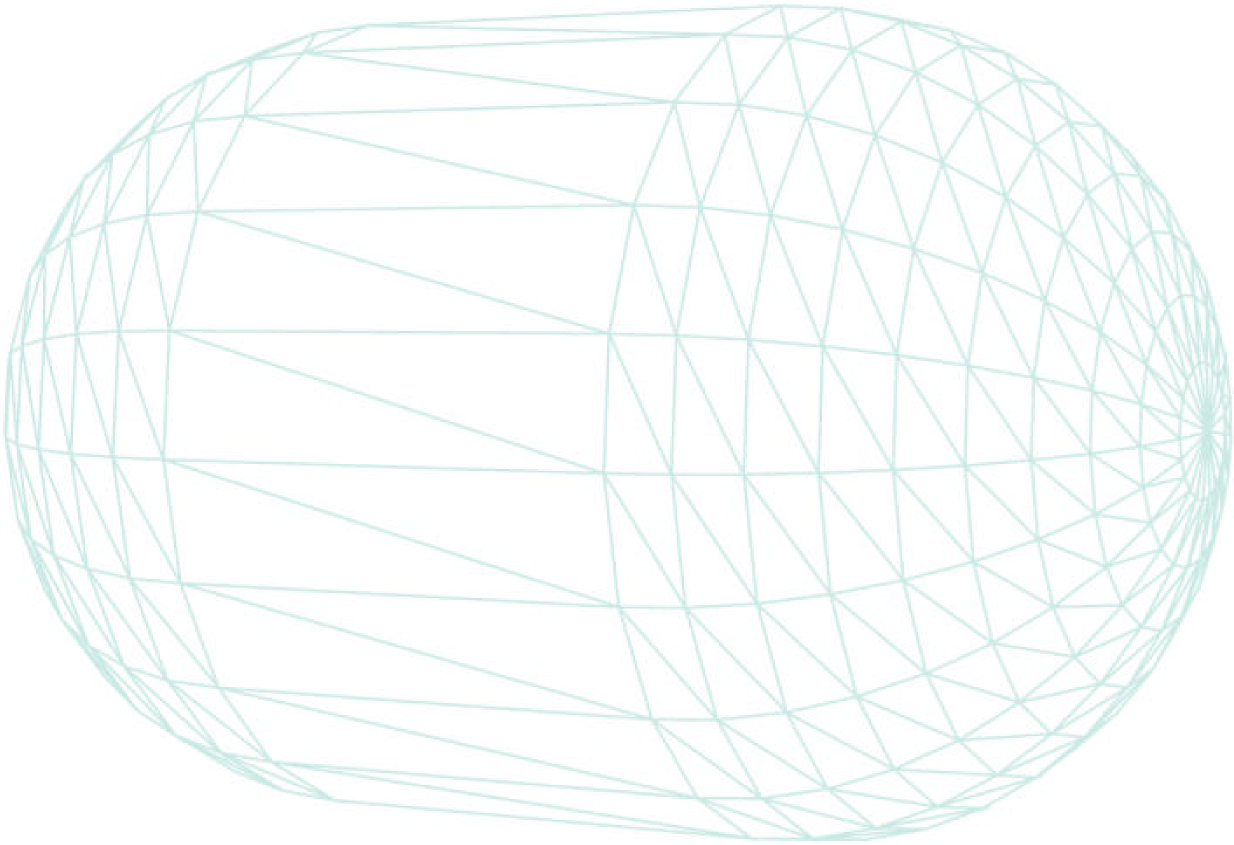


and segments of vibrating string. String theory successfully produces a quantum version of gravity, but not one that connects with our world in an obvious way. Nor does it resolve those fundamental conceptual problems. String theory's leading rival, loop quantum gravity, is an attempt to directly quantise general relativity. Loop proponents typically take the conceptual challenges of quantum gravity more seriously than their stringy colleagues, but the challenges remain.

This has led some physicists to take a step back and ask the question in a different way. The standard approach to developing a quantum description of some phenomenon, like the electromagnetic field or a collection of atoms, is to start with a classical description and then "quantise" it. That approach has failed again and again when it comes to gravity and space-time. It also isn't how nature works. The real world doesn't start classically and then somehow quantise. It is quantum from the start, and the classical world emerges as an approximation.

So maybe we shouldn't be trying to quantise gravity at all. Perhaps we should instead formulate a quantum theory from the start, and then show how classical space-time emerges from that. It is a new approach that has dramatic consequences for how we think about what space-time itself is made of.

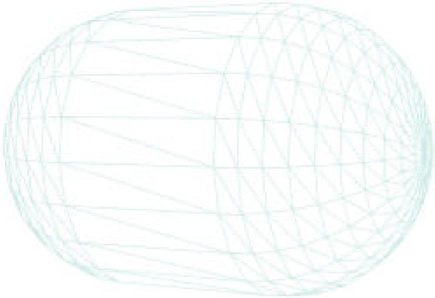
To make progress in this direction, it is helpful to start with our current best physical theory, which is quantum field theory. According to this theory, the fundamental ingredients of the world are fields, such as the electric and magnetic fields. Even particles like electrons and quarks are simply vibrations in fields that stretch through space.

Classically, we can specify the value of a field in an approximate fashion by dividing space into tiny regions, then listing the value of the field in each region. Once we graduate to quantum field theory, an extra feature comes into the game: the values of the field in different regions can be entangled with each other. Due to quantum uncertainty, we don't know exactly what answer we will get if we measure the field at some location, but entanglement means the answer we get at one point will affect what we would measure at any other point.

In the vacuum state of an ordinary quantum field theory – empty space, no particles flying around – the entanglement between fields in different regions is directly tied to the distance between them, and therefore to the geometry of space-time. Nearby regions are highly entangled with each other, while faraway regions share little entanglement.

This suggests an intriguing way to reverse our normal way of thinking and so find space-time within quantum theory. Let us imagine starting with just a quantum state, no pre-existing notion of space-time. Now we can try to work backwards, to extract space-time from entanglement.

If in ordinary physics the entanglement between two regions goes down as the regions get further apart, let



"The real world is quantum, and the classical world arises as an approximation"

us imagine defining the distance as (inversely) related to the entanglement. In that case, having a quantum state automatically gives us the "distance" between any two parts of it, and therefore defines a geometry on this emergent space.

So far so good. But a quantum state exists at each moment of time, so at best it can define the geometry of space at that moment. We want to extend this to four-dimensional space-time.

Thankfully, here we can borrow a trick from physicist Ted Jacobson at the University of Maryland, who, in 1995, showed how we could derive Einstein's equation for general relativity from simple assumptions about the relationship between entropy and geometry.

Entropy, a measure of disorder, is directly related to entanglement: the more entangled a region is with the rest of the world, the more entropy it contains. Einstein said that it is adding matter or energy to a region that causes space-time to curve. Jacobson showed that increasing the entanglement of a region can have the same effect, if we insist that the amount of entropy must be proportional to the area bounding that region. That is automatically true in empty space, but Jacobson suggested that it remains true even when space isn't empty. You can try to add more entanglement, but space-time will bend to compensate, so that entropy always remains proportional to area.

So Einstein says that energy causes curvature, while Jacobson says entanglement does. But Jacobson also argued that it is really the same thing: whenever you add entanglement, energy necessarily follows. From this logic, he was able to derive that the curvature of space-time in his approach obeyed the same equation that Einstein first wrote down for general relativity. Gravity, it appears, can arise from entanglement, rather than directly from mass and energy. This remarkable result was the beginning of what is now called "thermodynamic" or "entropic" gravity.

But it doesn't quite get us to where we need to be. In deriving his alternative picture of where gravity comes from, Jacobson assumed a classical space-time and imagined that there were quantum fields living within it. Ideally, we would like to keep everything quantum from the start and derive the existence of space-time itself. This is something I have attempted with my collaborators, ChunJun (Charles) Cao and Spiros Michalakis at the California Institute of Technology. Rather than starting with vibrating quantum fields living in space-time, we started with completely abstract quantum "degrees of freedom".

This is just some quantity that can take on different values, independently of other quantities. In Newtonian mechanics, the degrees of freedom are positions and velocities of particles; in field theory, they are the values and rates of change of the fields. In our approach, the degrees of freedom don't have any direct physical interpretation. They are the basic stuff of reality, the essence out of which everything else is made – a kind of "quantumness" that pre-exists everything. Most importantly, these quantum

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degrees of freedom are entangled with each other.

With that in mind, we flip around Jacobson's idea. Now we can define the area surrounding a region as the entanglement of its degrees of freedom with the outside world. And sure enough, the corresponding geometry obeys Einstein's equation of general relativity. Gravity, in other words, can emerge directly from the quantum essence of reality, without quantising any assumed classical stuff.

That might sound like a conclusion, but it is more like a promising beginning. Many assumptions went into our derivation, and whether these assumptions hold true in nature remains to be seen. Most importantly, our derivation of Einstein's equation from entanglement only works when gravity is weak and space-time is nearly flat. Once gravity becomes strong and space-time is curved, as in the Big Bang or near a black hole, radically new phenomena become important.

The most dramatic of these is the "holographic principle," the idea that the degrees of freedom describing a black hole can be thought of as living on its edge, the event horizon, rather than the interior. Juan Maldacena of the Institute for Advanced Study in Princeton used the holographic principle to show an equivalence between two very different theories: quantum field theory without gravity in four-dimensional space-time, and quantum gravity with a negative vacuum energy in five dimensions.

Subsequent work by Mark van Raamsdonk at the University of British Columbia in Canada and others has shown that the space-time geometry on the quantum-gravity side of this correspondence is directly tied to quantum entanglement on the field-theory side. As we decrease entanglement in the field theory, space-time on the quantum-gravity side grows apart.

Maldacena and Leonard Susskind at Stanford University in California have taken this connection to extremes with a bold idea they dubbed "ER = EPR." ER stands for Albert Einstein and Nathan Rosen, who wrote a paper in 1935 proposing the existence of wormholes, or shortcuts through space-time. EPR, meanwhile, stands for Einstein, Boris Podolsky and Rosen, who collaborated on another paper emphasising the role of entanglement in quantum theory. The ER=EPR conjecture therefore posits that whenever you have two entangled particles, there is a tiny wormhole connecting them.

Don't take this too literally. The wormholes that purportedly connect pairs of particles would be microscopically small and impossible for anything to pass through. It is only when massive amounts of entanglement become involved that we begin to see a macroscopic distortion in the fabric of space.

Moreover, our universe has a positive vacuum energy, not a negative one, so the implications of the equivalence revealed in Maldacena's negative-vacuum-energy thought experiment don't translate directly to an actionable strategy for dealing with quantum gravity in the real world. They do, however, serve as another strong hint that quantum entanglement is at the heart of it all.

All of these ideas are, at present, somewhere between promising conjectures and optimistic dreams. We don't know the best way to think about these supposed fundamental degrees of freedom that entangle together to make space-time, nor do we know how they interact with each other in any detailed way. We can't yet derive the emergence of quantum fields living within space-time, obeying the rules of relativity. And we certainly can't answer important questions like why the energy of empty space is so small, or why space has four macroscopic dimensions.

Even so, imagining that space-time emerges from quantum entanglement is a promising way to think about the basic nature of reality. It may be that it was a mistake to start with general relativity and try to quantise it; maybe space-time was lurking within quantum mechanics all along. ▮

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